

ENGER

The Distribution of Pressures
through Non-Cohesive Materials

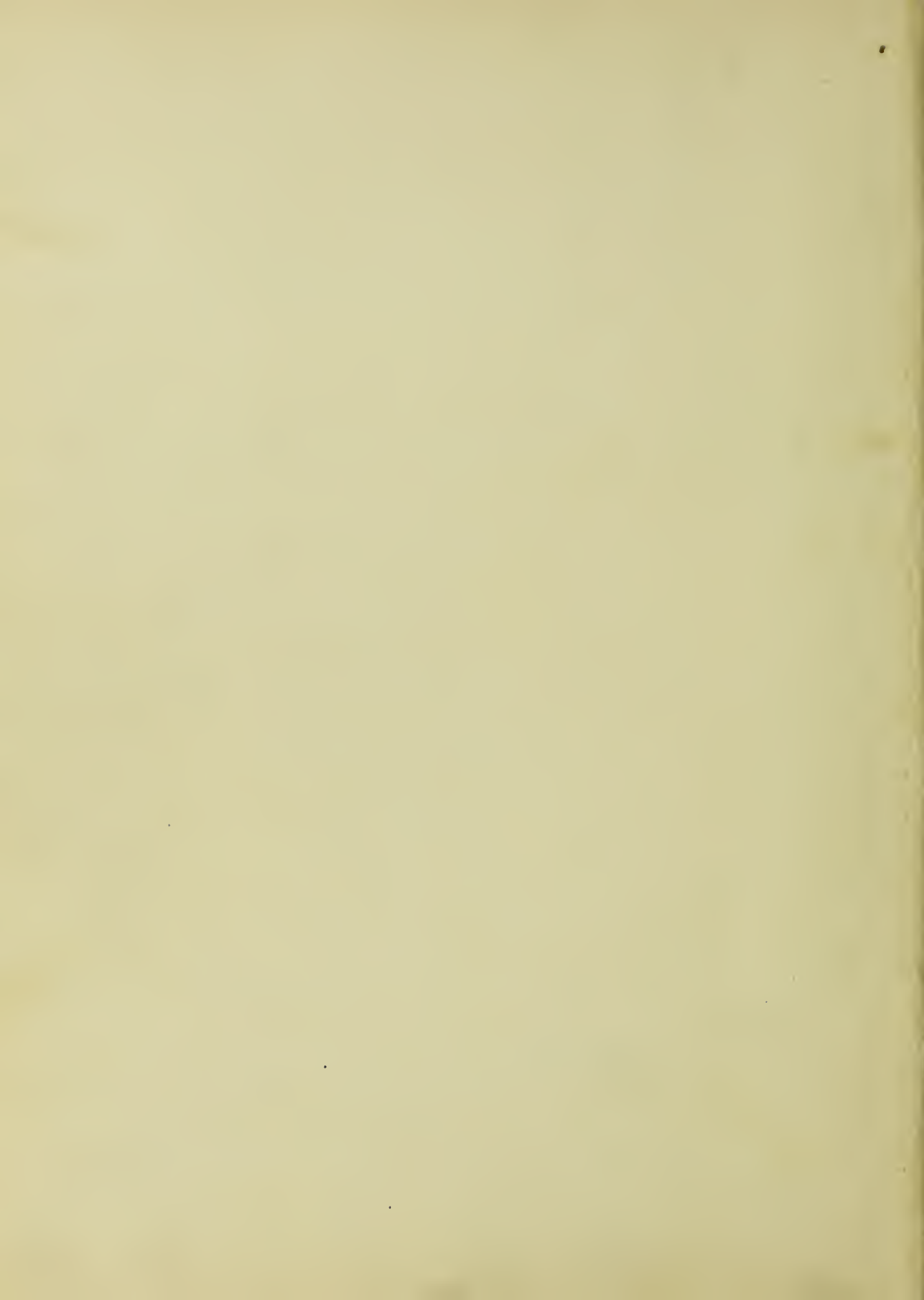
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THE DISTRIBUTION OF PRESSURES THROUGH
NON-COHESIVE MATERIALS

BY

MELVIN LORENIUS ENGER

B. S. University of Illinois, 1906.

C. E. University of Illinois, 1911.

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

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IN THEORETICAL AND APPLIED MECHANICS

IN

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June 2, 1917

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPER-
VISION BY MELVIN LORENIUS ENGER
ENTITLED THE DISTRIBUTION OF PRESSURES THROUGH NON-COHESIVE
MATERIALS
BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE IN THEORETICAL AND APPLIED MECHANICS.

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In Charge of Thesis

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Recommendation concurred in:*

Committee

on

Final Examination*

*Required for doctor's degree but not for master's.

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THE DISTRIBUTION OF PRESSURES THROUGH NON-COHESIVE MATERIALS

By Melvin Lorenius Enger.

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I. INTRODUCTION

THE DISTRIBUTION OF PRESSURES THROUGH NON-COHESIVE MATERIALS.

Preliminary. The object of this thesis is to record and analyze the results of experiments on the transmission of pressure through granular material; such as sand, gravel and broken stone; beneath railroad ties and also beneath circular bearing plates. The experiments form a part of the general investigation of the Joint Committee on Stresses in Railroad Track, of which Professor A. N. Talbot is chairman. The experiments have been made under the supervision of Professor Talbot and under the immediate direction of the writer.

Earlier Experiments at Illinois. Experiments on the distribution of pressure beneath circular bearing plates have been carried on as thesis work by K. A. Burnell, 1910; W. C. Eells and J. Van Dervoort, 1911; L. N. Fisher and H. F. Wagner, 1912; A. W. Kimbell and M. C. Taylor, 1913. The results obtained were of interest and the experience gained was very helpful in planning the more elaborate experiments reported in this thesis.

It will be of interest to examine briefly the results of some of the earlier experiments at Illinois, and to compare them with some experiments made at Pennsylvania State College. The following discussion, by the writer, was published in the Engineering Record, Vol. 73, p. 106; Railway Age-Gazette, Vol. 60, p. 321; Engineering and Contracting, Vol. XLV, p. 53; and the Railway Review, Vol. 58, p. 129.

II. PREVIOUS ILLINOIS EXPERIMENTS.

A sectional view of the apparatus used in most of the tests is shown in Fig. 1. A concrete slab, 9 ft. x 8 1/2 ft. x 16 in., was used to support the sand. A rectangular opening 6 in. x 6 in. extends horizontally into the slab about 3 ft. 8 in. from one side. A short vertical opening having an internal diameter of 4 1/8 in. connects with the opening about 3 ft. from the edge of the slab. A 4-in. wooden plug, or plunger, with its upper surface flush with the top of the slab, fits loosely in the vertical opening and rests on knife-edge on a 3-in. I-beam in the horizontal opening. The I-beam acts as a lever transmitting the load on the plug to a platform scale. The ratio of the load weighed on the scales to the load on the plug is as 1 : 8.09. In some of the experiments the vertical pressure transmitted through the sand was measured by means of the water pressure under a 6-in. diaphragm which was placed flush with the surface of the slab. A flange with a beveled edge was screwed to the top of a 6-in. pipe and a diaphragm of packing rubber was clamped over the beveled edge by means of a beveled collar. The 6-in. pipe was connected to a pressure gage by means of a short 3/4-in. pipe line. The loading device of the apparatus was movable and in order to get pressures away from the axis of the applied load the loading device was shifted to any desired position. In the apparatus used in the earlier experiments the sand rested on a plank floor laid on closely spaced I-beams, but the results were not entirely satisfactory. It is thought that the yielding of the floor had a considerable effect upon the distribution of the pressure.

In most of the experiments the load was applied to the sand through a circular plate 13.5 inches in diameter. Circular plates 9 and 21 inches in diameter were also used. The load was applied by means of a hydraulic jack which reacted against a 20-in. I-beam connected with the slab by means of four 1-in. steel rods. The load was weighed with a calibrated steel spring whose deflection was indicated on an Ames dial gage.

Experiments were made with depths of sand of 6, 12 and 18 inches. Pressures were determined with the center of the vertical axis of the plug (or diaphragm) directly below the center of the load and also with horizontal distances of 3, 6, 12 and 18 inches between them.

For any test the sand was thoroughly compacted before taking readings. For example, when experiments were being made on a depth of sand of 12 inches, the plate was started on a layer of sand about 15 inches deep and forced down to the 12-in. depth. The load was then released and applied several times and readings were taken of the applied load and of the load transmitted to the plug.

In order to determine the effect of the size of the area loaded upon the way the pressure is transmitted through the sand the load was applied to plates 9-in., 13.5-in. and 21-in. in diameter and measured with the 6-in. diaphragm. In these experiments the center of the diaphragm was directly below the center of the plate to which the load was applied. The results of these tests are summarized in Fig. 2. It will be noted that the size of the loaded area has an important effect upon the proportion of the applied average unit-pressure transmitted

through sand of a given depth to the diaphragm. In these tests the 21-in. plate carried loads up to 18,000 lb., the 13.5-in plate loads up to 9,000 lb. and the 9-in. plate loads up to 2,500 lb.

In Fig. 3 the average values of the ratio of the unit-pressure on the 6-in. diaphragm to the average unit-pressure applied to the loaded area are plotted as ordinates and the diameter of the loaded area as abscissas, using logarithmic scales. It will be seen that parallel straight lines pass through the points which are plotted for each given depth of sand. From the slope of the lines it is found that the proportion of the applied average unit-load which is transmitted through the sand of a given depth to a diaphragm directly below varies as the 1.86 power of the diameter of the loaded area. It follows, for example, that if a load is applied to a plate 9-in. in diameter such that the intensity of pressure on a small area at a certain distance directly below the center of the plate is 10 lb. per sq. in., then if the same total load is applied to a plate 21-in. in diameter the intensity of pressure on the same small area would be 8.9 lb. per sq. in. That is, by increasing the area carrying the load 5.44 times, the intensity of the pressure in the sand directly below the plate at a given depth has been decreased but little, a conclusion very different from the usual assumptions.

No experiments were made by the plug method to determine the effect of the diameter of the loaded area on the intensity of the vertical pressure at any given depth. According to the plug experiments made with the 13.5-in. plate, the ratio which the intensity of pressure directly below the center of the

loaded area bears to the average applied load varies inversely as the 1.95 power of the depth of the sand above the plug.

Assuming that this relation holds for other diameters of loaded area and combining this result with the effect of the variation in diameter previously described, the following equation was found:

$$p = 91 \frac{d^{1.86}}{h^{1.95}}$$

in which p is the ratio, expressed in percent, which the intensity of the transmitted pressure at a point h inches directly below the center of the loaded area bears to the average applied unit-load, and d is the diameter of the plate in inches. The equation represents roughly the results of the experiments, but it is not probable that it has general application.

In the experimental work the diaphragm has been found to be a less satisfactory method for measuring the transmitted pressure than the method of weighing the load on the plug. The reason is that the diaphragm becomes distorted when load is applied, the center being depressed and the outside portion raised by the water pressure, and the distortion increases with a repetition of the load. For off-center loadings the depression occurs in the part of the diaphragm nearest the center line of the applied load, while the part farthest away is forced up. So much trouble was experienced with the bursting of the diaphragm that it could not be used for off-center loads on thin layers of sand.

In Fig. 4 and Fig. 5 have been plotted curves showing the intensity of the transmitted pressure at different distances from the center line of the applied load in terms of the applied

average unit load, as determined by experiments in which the transmitted pressure was measured by the 4-in. plug, Fig. 4 being for a depth of sand of 6 inches and Fig. 5 for 12 inches. The curves are of interest in showing the lateral distribution of pressure over a horizontal plane at a given depth. Dotted lines giving the results of experiments made at Pennsylvania State College, and reported by J. A. Moyer in the Engineering Record of May 30, 1914 and March 13, 1915, are also plotted in the two figures. In the Pennsylvania experiments the load was applied to an area 12-in. x 12-in. and the pressure was measured on a plug of the same size. The measured pressure was therefore the average over a relatively large portion of the base. The Illinois and Pennsylvania experiments have one inconsistency in common: the sum of the upward pressures under a 6-in. layer of sand exceeds the sum of the applied load and the weight of the sand. The reason in the case of the Illinois experiments is that center loadings were taken first, leaving a pillar of compacted sand above the plug which carried more than the average pressures to the plug for the off-center loadings which followed. For depths greater than 6-inches the effect of the compacting was not so great. It is probable therefore that the readings at 3 inches and 6 inches away from the center are too high for the 6-inch depth of sand.

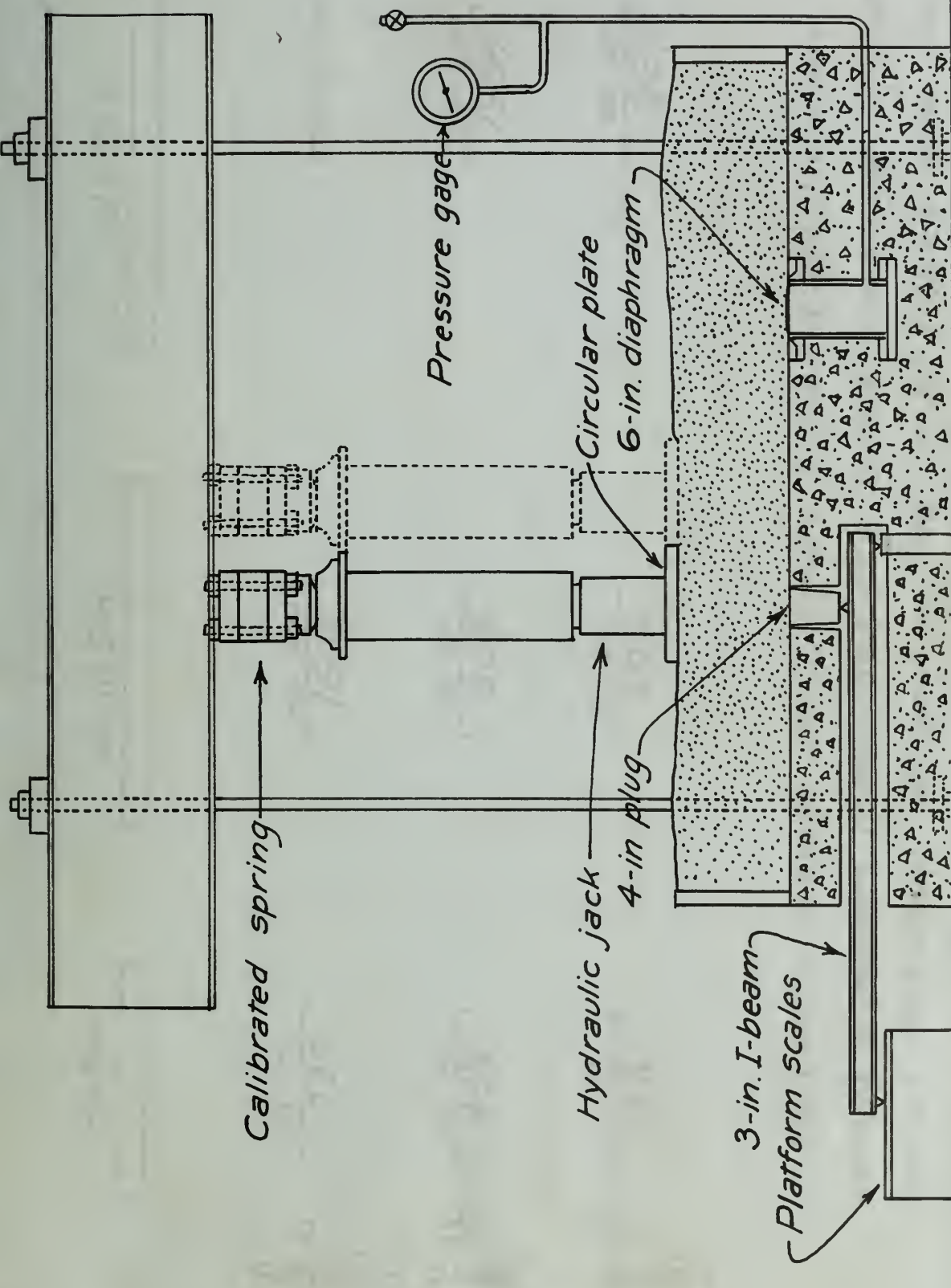
In Fig. 6 the results of the experiments are plotted to show lines of equal vertical pressure in the sand below the plate. The line of zero vertical pressure has been drawn downward on a 1 : 2 slope, and an inspection of the experimental results indicate that vertical pressures outside this line are very small.

It will be noted that the region below the center of the load is one of high pressure, a fact of importance which seems generally to have been overlooked. The diagram is instructive in showing the manner of the distribution of the vertical pressure at different depths and different distances from the axis of the load. It is seen that the pressure on any horizontal plane is far from uniform.

Messrs. Fisher and Wagner took a number of photographs which show the direction of movement of the sand under the action of a load. Some of the photographs are shown in Fig. 8 to Fig. 17. The arrangement used in making the photographs is shown in Fig. 7. Sand was piled against a sheet of glass and the camera was placed about three feet from the glass on the block shown in the picture Fig. 7. Time exposures of from 60 to 90 seconds duration were taken while the blocks were forced slowly and uniformly into the sand. As the sand moved elongated images of the grains were formed on the photographic plate. The lines formed in this manner therefore show the direction of the movement of the sand for various conditions of loading.

In Fig. 8 lines of equal vertical pressure from Fig. 6 have been plotted on the photograph.

Some of the photographs are suggestive in showing the manner in which the ballast under a railroad tie is affected by the loading and spacing of adjacent ties which restrain the horizontal movement of the ballast.



Arrangement of apparatus.

FIG. 1.

$$d = 9 \text{ in}$$

$$d = 13.5 \text{ in.}$$

$$d = 21 \text{ in.}$$

Depth of sand - inches

$$\frac{70 - 75}{72\%}$$

$$\frac{140 - 200}{160\%}$$

$$\frac{140 - 200}{160\%}$$

$$\frac{36 - 50}{43\%}$$

$$\frac{87 - 95}{90\%}$$

$$\frac{189 - 200}{195\%}$$

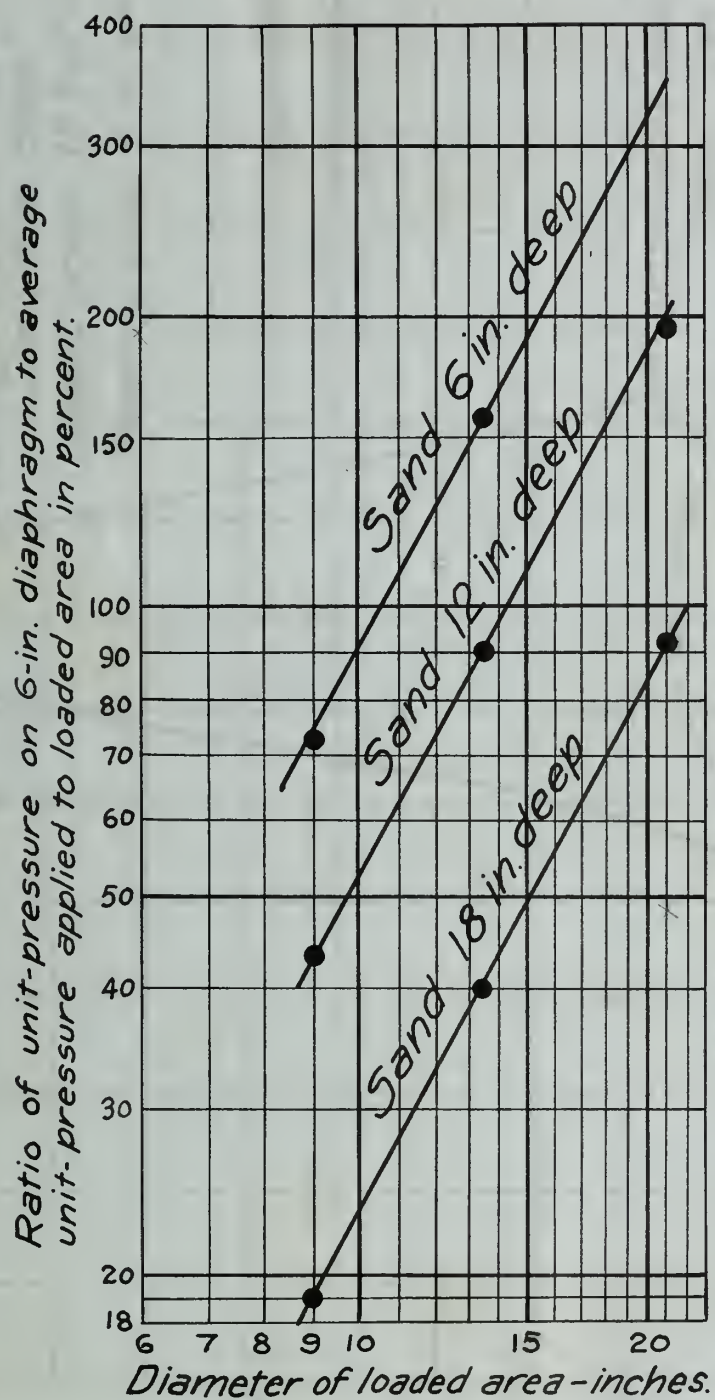
$$\frac{17 - 21}{19\%}$$

$$\frac{35 - 54}{40\%}$$

$$\frac{90 - 94}{92\%}$$

Percent of average unit pressure applied to circular areas of various diameters transmitted to a 6-inch diaphragm through various thicknesses of sand. The small figures show the range and the large figures the average values.

FIG. 2.



Curves showing the relation between the diameter of the loaded area and the load transmitted to 6-in diaphragm.

FIG. 3.

The following table shows the results of the
 experiments conducted on the effect of the
 concentration of the solution on the rate of
 reaction. The temperature was kept constant
 at 25°C.



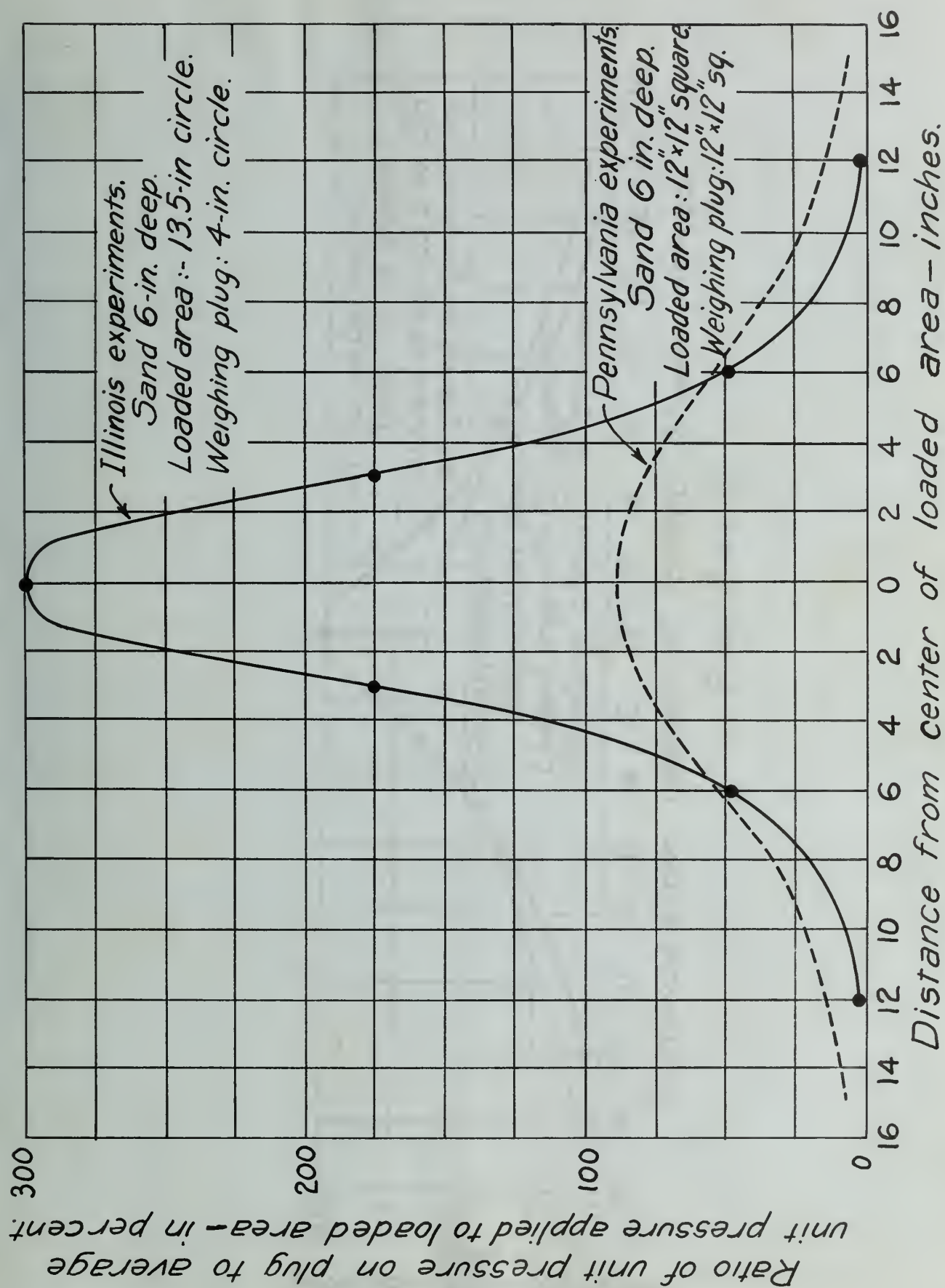


FIG. 4.

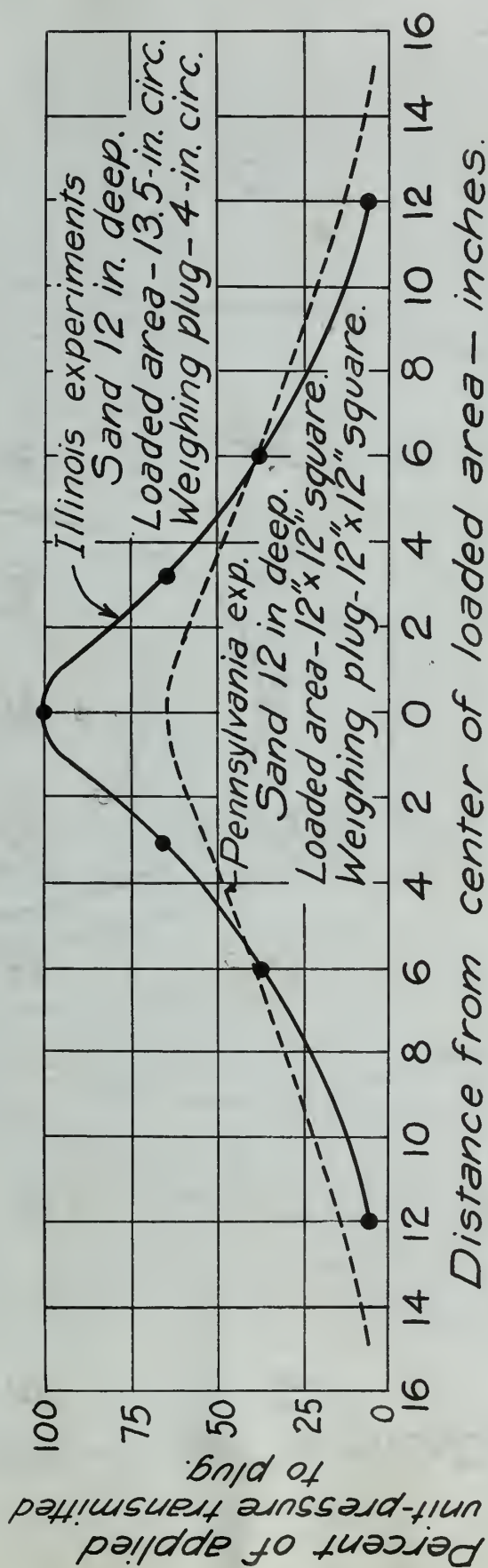
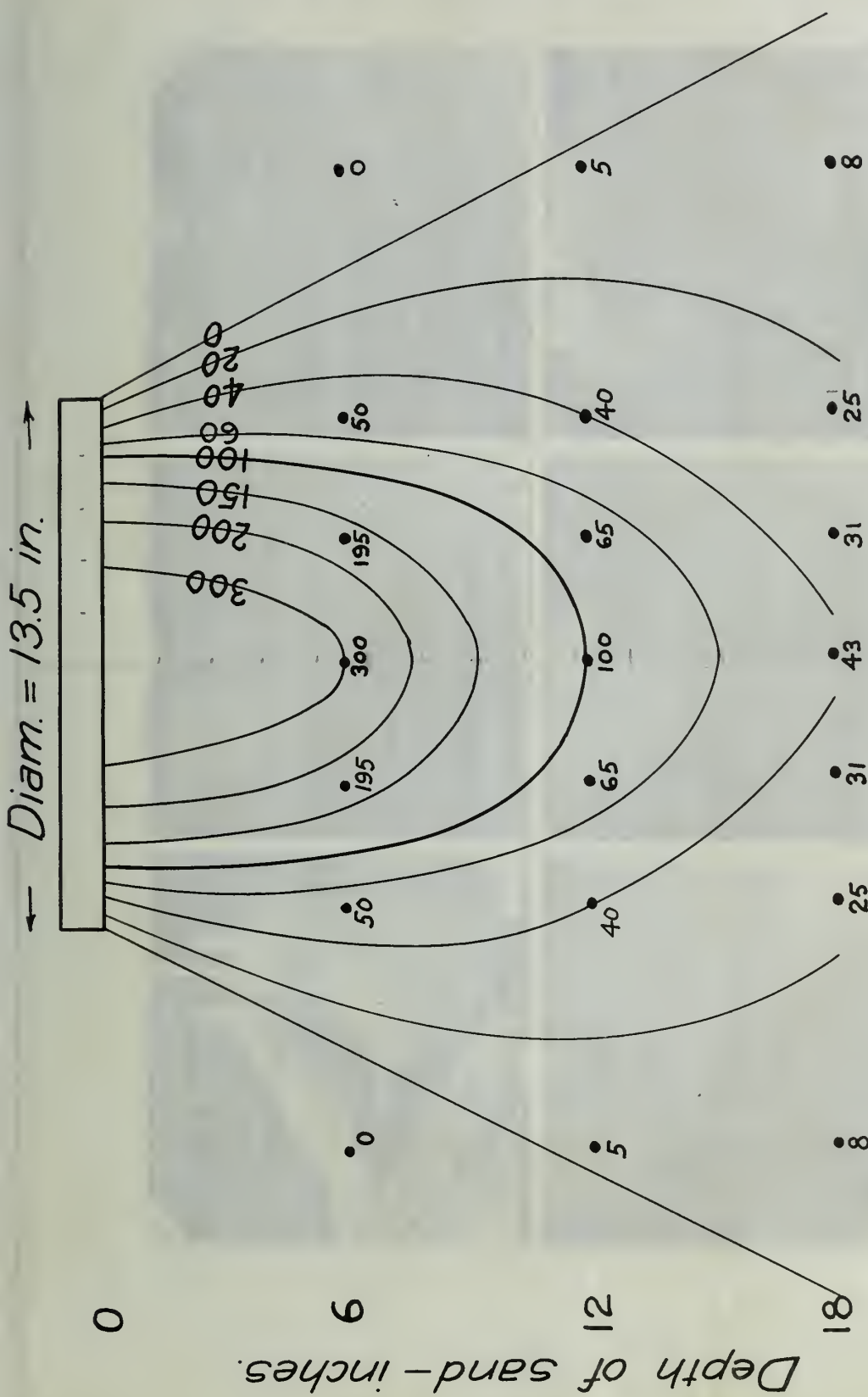


FIG. 4a.

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Lines of equal vertical unit-pressure - expressed as the percent which the average vertical unit-pressure on the 4-in. plug is of the average unit-pressure applied to loaded area.

FIG. 5.



Fig. 6

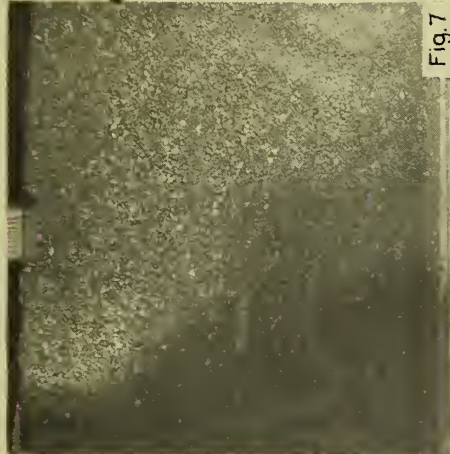


Fig. 7

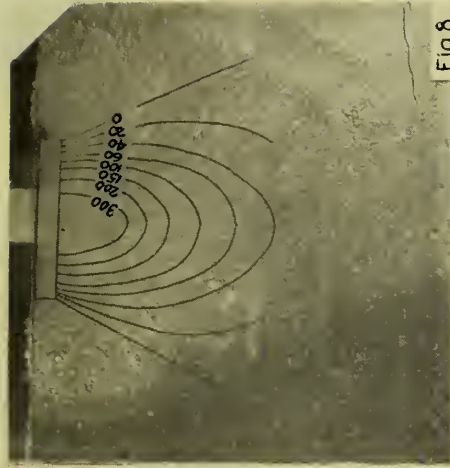


Fig. 8



Fig. 9



Fig. 10

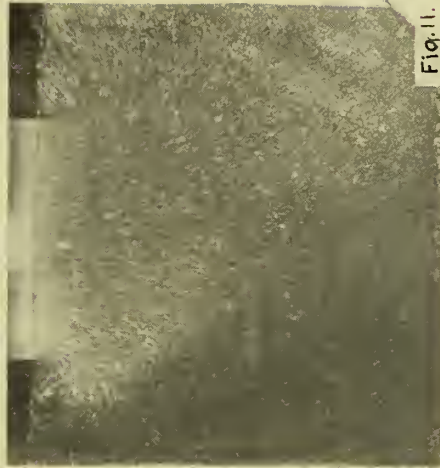


Fig. 11

Fig. 6- Arrangement for making sand-movement photographs. Fig. 7- Sand before application of load. Fig. 8- Limes of equal vertical pressure from Fig. 5 plotted on photograph showing movement of sand under block 8 in. wide. Figs. 9, 10, 11- Photographs showing direction of movement of sand under action of single load; Fig. 9, 2-in. block; Fig. 10, 4-in. block; Fig. 11, 10-in. block.

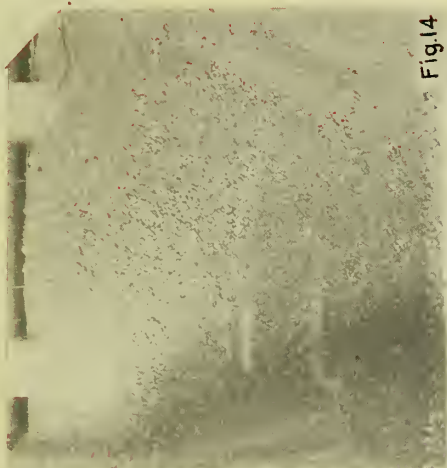


Fig. 14

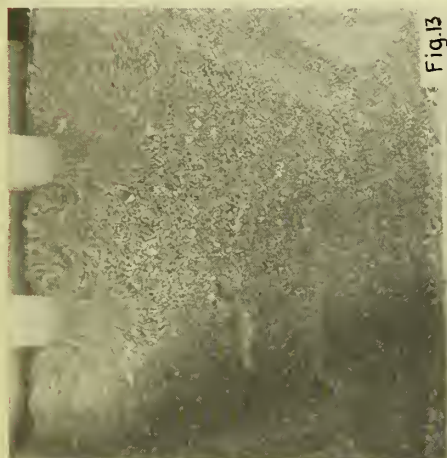


Fig. 13

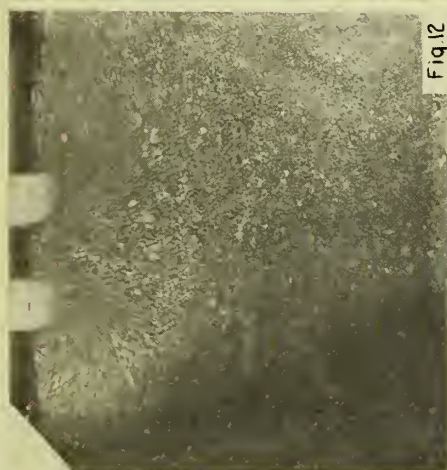


Fig. 12

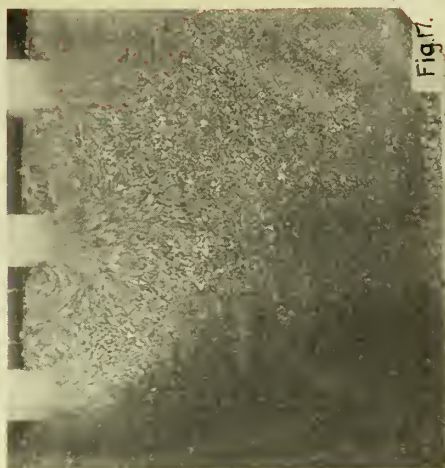


Fig. 17

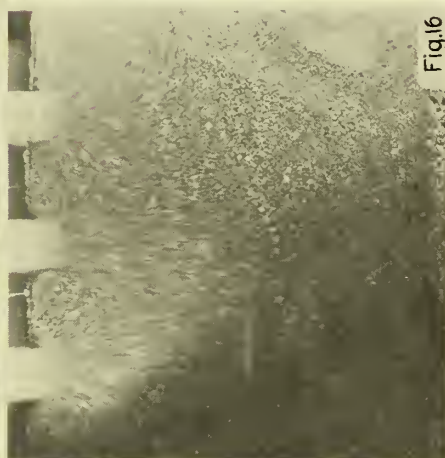


Fig. 16

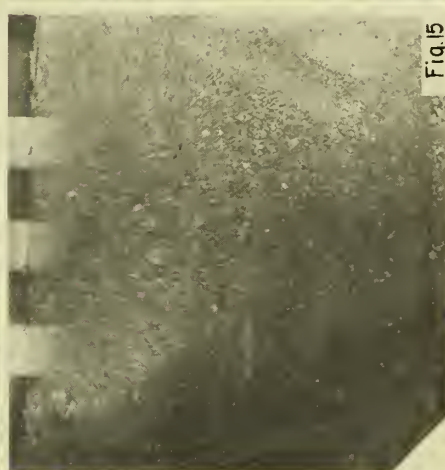


Fig. 15

Figs. 12, 13, 14- Direction of movements of sand under action of two loads: Fig. 12, 2-in. blocks, 4 in. on centers; Fig. 13, 2-in. blocks, 6 in. on centers; Fig. 14, 2-in. blocks, 12 in. on centers. Figs. 15, 16, 17- Direction of movement of sand under action of three loads: Fig. 15, 2-in. blocks, 4 in. on centers; Fig. 16, 2-in. blocks, 6 in. on centers; Fig. 17, 2-in. blocks, 8 in. on centers.

III. EXPERIMENTS MADE FOR THE JOINT COMMITTEE ON STRESSES IN RAILROAD TRACK.

Purpose of the Experiments. The experiments were made as a part of the work of the Joint Committee on Stresses in Railroad Track, to determine the pressures at various points in the ballast beneath railroad track. Experiments were also made with circular bearing plates. Experiments were made to determine the effect of: material used for ballast, moisture, spacing of ties, loading of ties, tamping, depth of ballast, repetition of load, and shape of ties.

Chronology. The tests herein reported were begun in November 1915 by Mr. J. Van Dervoort. They were continued during the spring of 1916 by Mr. G. H. Pike and Mr. A. W. Carlsen, and during the summer of 1916 by Mr. B. R. Ordonez and Mr. A. Rodriguez. Some work on the effect of repetition of load has been done during the present school year by student assistants: Messrs. C. B. Taylor, H. F. Vaughan, C. E. Sheppard and J. R. Hodge. All of the experiments have been under the supervision of Professor Talbot and under the immediate direction of the writer.

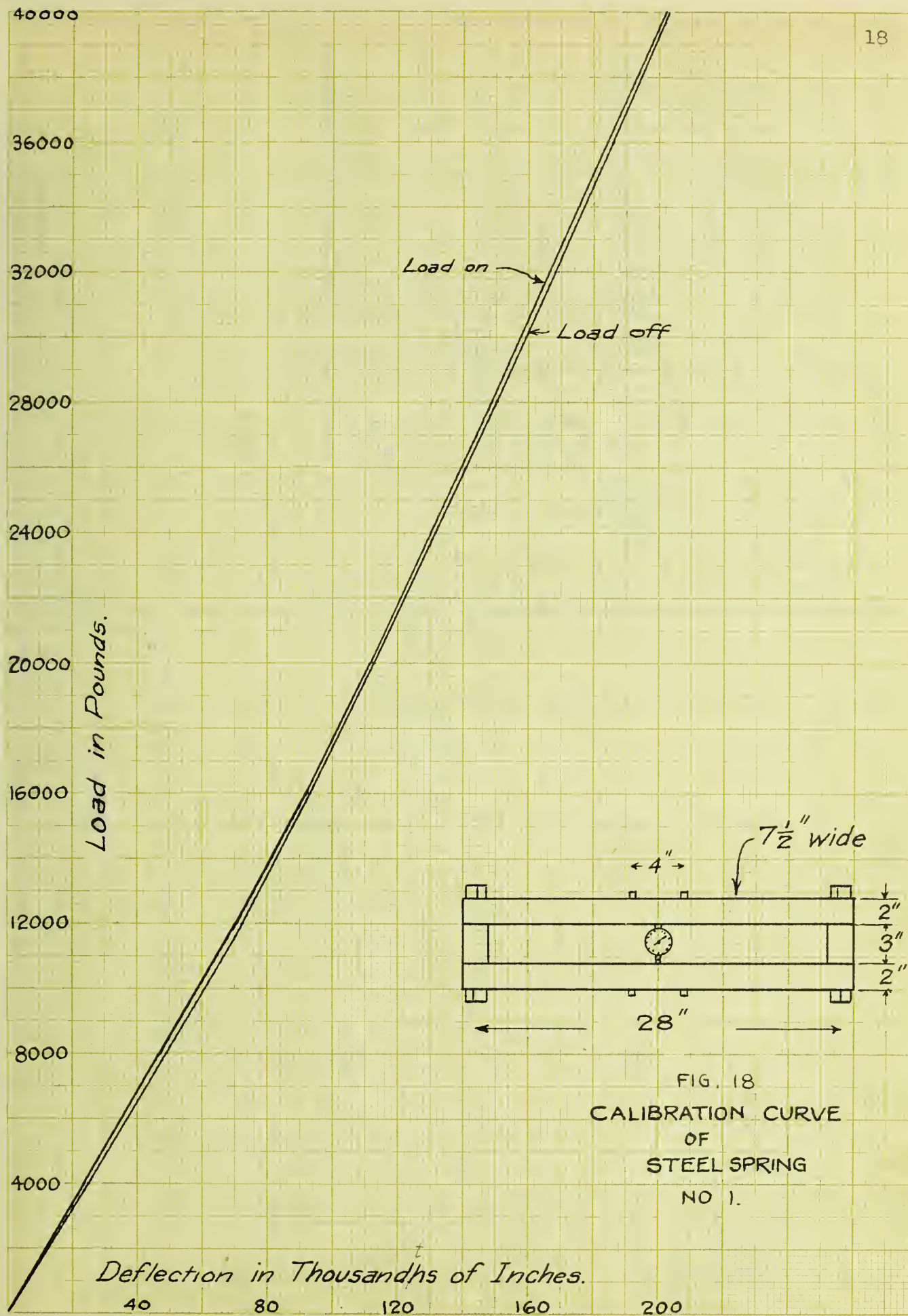
General Description of the Method of Testing. The general arrangement of the apparatus is shown in Fig. 19. The method of making the tests is similar to that already described as used in making the earlier experiments, except that "pressure capsules" were used for measuring the pressures in the ballast instead of a diaphragm or a plug. It was possible in this way to measure the pressure at a number of points simultaneously.

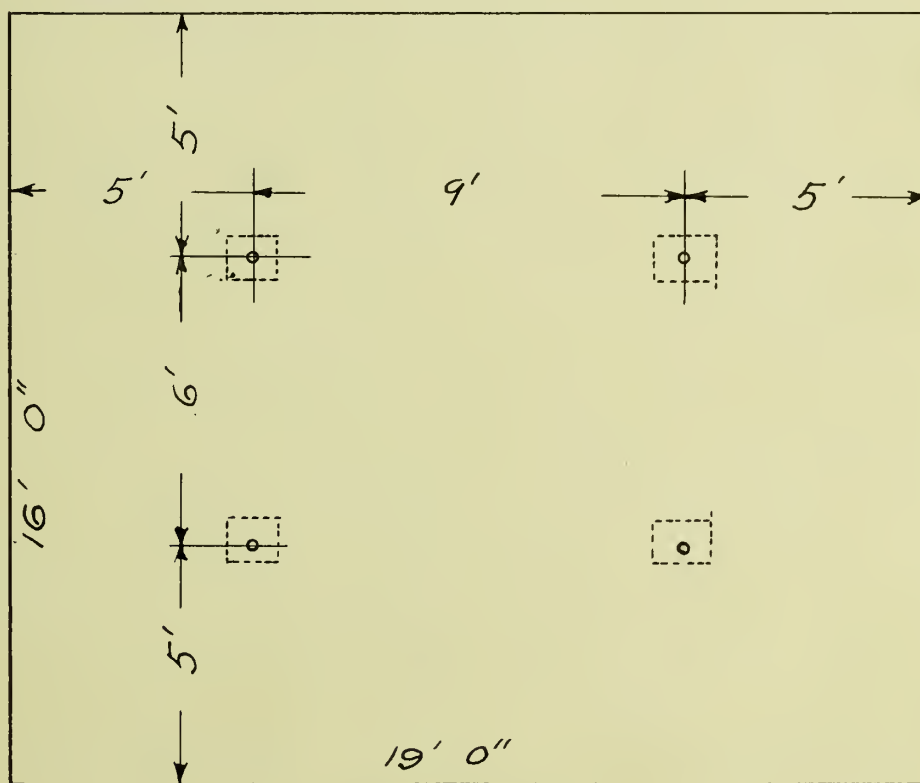
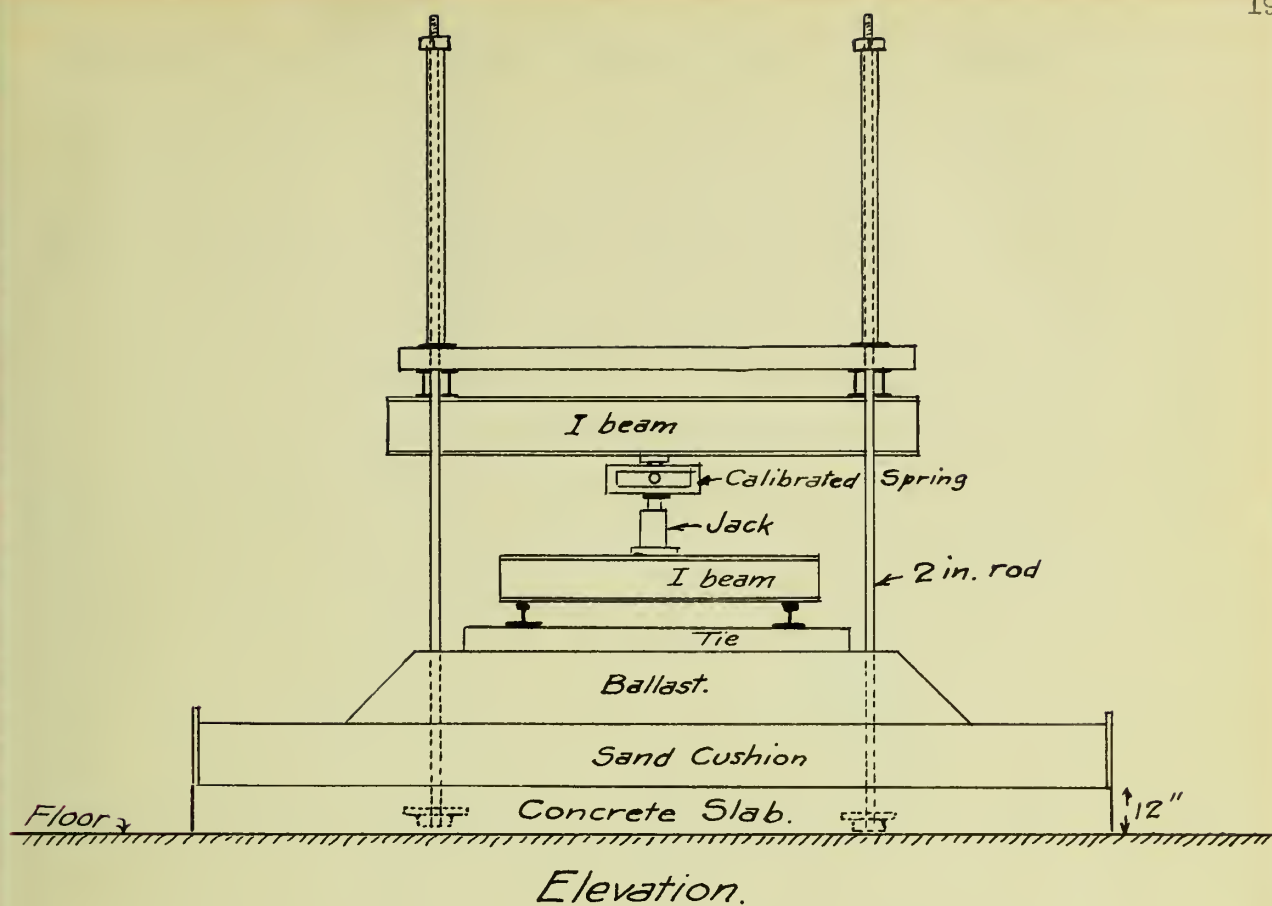
The location of the pressure capsules in the ballast is shown in the figures giving the results of the experiments. In the experiments with sand ballast the capsules were placed on the concrete slab and the ballast was placed over them. In one of the preliminary experiments the capsules were placed at different levels in the ballast, but in all of the later experiments the capsules were at the same level. In the experiments with rock ballast and with gravel ballast a sand cushion about 15 inches deep was placed beneath the capsules. Burlap was placed over the sand to keep the sand and the coarse ballast from mixing.

After the required amount of ballast had been placed, it was leveled off and the ties were placed. Three ties were used in most of the experiments. The load was applied to the ties by means of a jack acting through a system of levers. One such arrangement is shown in Fig. 27, other arrangements are shown in some of the photographs. By varying the position of the bearing strips the loads carried by the ties could be apportioned as desired. In some of the experiments only one tie was loaded.

The load was weighed by means of a calibrated steel spring whose deflection was measured by means of an Ames dial gage. The construction of the spring and its calibration curve is shown in Fig. 18.

Before taking readings loads were applied to the ties by means of the jack several times in order to compact the ballast. The zero readings of all of the pressure capsules were then taken. A load was then applied to the ties and the





Plan of Slab

FIG. 19.
ARRANGEMENT OF APPARATUS

Ames dials on the pressure capsules were read and recorded.

Ames dials were also used to determine the vertical movement of the middle tie. The load on the ties was then increased and the process repeated. The maximum load was determined by the limit of the capacity of the jack, or the limit of the capacity of one or more of the pressure capsules, or by the "yield point" of the ballast (as shown by rapid sinking of the ties without the addition of much load). After readings had been taken at the maximum load, the load was decreased and one or more sets of readings taken. Readings were then taken with all load removed from the ties and another series of readings taken for the same loads as in the first series. Experiments were continued until there was a fair agreement in the readings of the capsules for any given load. Three or more sets of readings were usually taken.

The Pressure Capsule. The pressure capsule was designed by Professor H. F. Moore and Mr. H. R. Thomas. For measuring the pressure the amount of the elastic deflection of a thin steel diaphragm is used. The pressure to be measured is received on the circular plate P (Fig. 20), which has an area of 5 square inches; the pressure is transmitted to the thin steel diaphragm D which is fastened by screws around its circumference to the cast iron box B. The screw S which fastens the plate P to the diaphragm D is hardened and bears on the knife edge of a small bell crank lever L which is pivoted at Q. The vertical deflection of the center of the diaphragm is transmitted by the bell crank lever, magnified, in a horizontal direction to the rod R which slides in the guides NN' and is enclosed in a horizontal tube K,

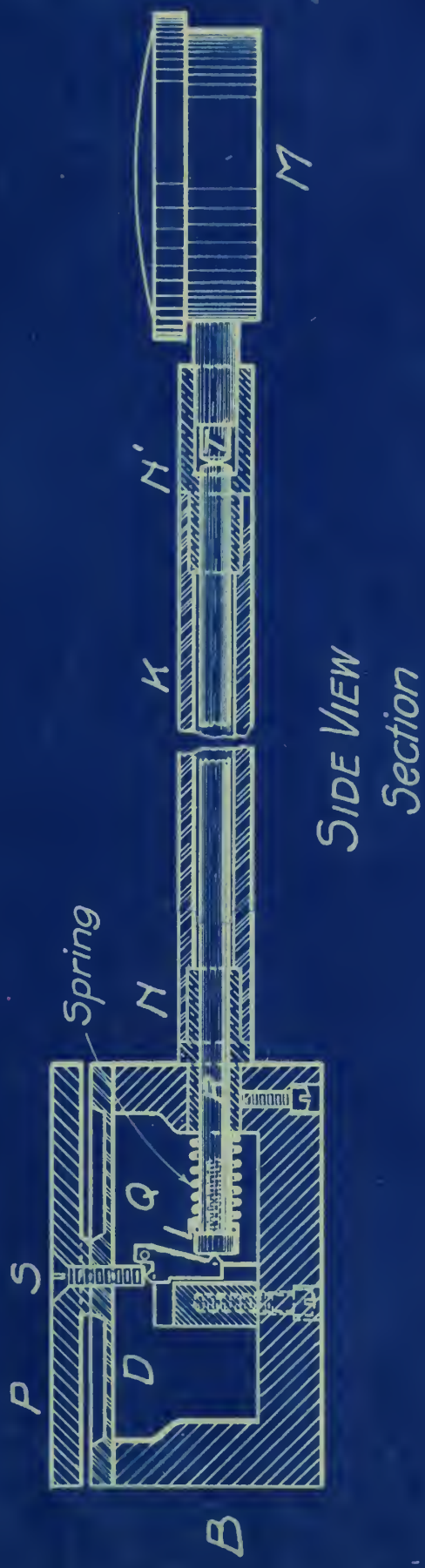
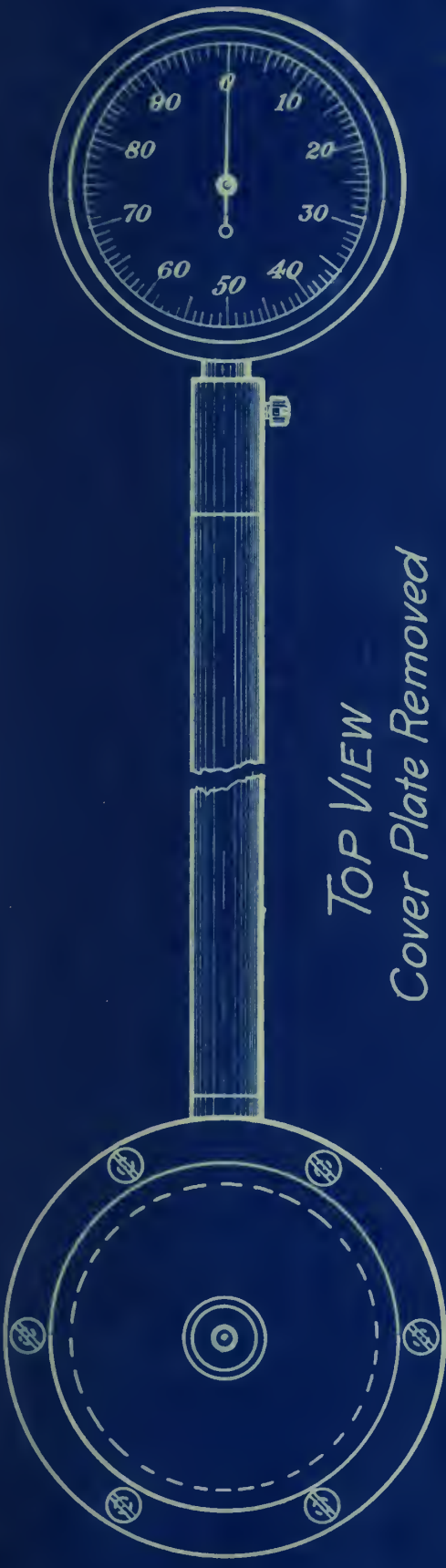


FIG. 20
THE PRESSURE CAPSULE



and finally bears against the plunger T of an indicating micrometer dial (Ames dial gage), whose movement is thus a measure of the elastic deflection of the diaphragm D. If the material of the diaphragm is not stressed beyond its elastic limit the deflection of the center of the diaphragm, and the consequent movement of the pointer of the micrometer dial, will measure the load on the plate P. Tape was wrapped around the capsule to prevent sand from getting under the plate P.

Each pressure capsule was calibrated, after it was taped, by placing it on a platform scale, and applying pressure by means of a screw clamp. Calibration curves for the capsules used in one series of experiments are shown on pages 23 to 26 inclusive.

During the course of the experiments it has been found advisable to modify a few minor features of the design of the capsule. It was found that the pipe K has a tendency to pull out of the capsule, causing negative readings. This has been remedied by threading the end of the pipe and screwing it into the capsule. Even this did not prove sufficient in the case of rock ballast. It was found necessary to protect the pipe K from the action of the ballast by enclosing it in a 1/2 in. pipe.

It has been found necessary to calibrate the capsules from time to time. This has been done each time before replacing a capsule in the ballast. Excessive loads and eccentric loads are the causes of the change of calibration.

Some of the pressure capsules had to have very long rods in order to extend beyond the ballast. These have been found to be rather sluggish.



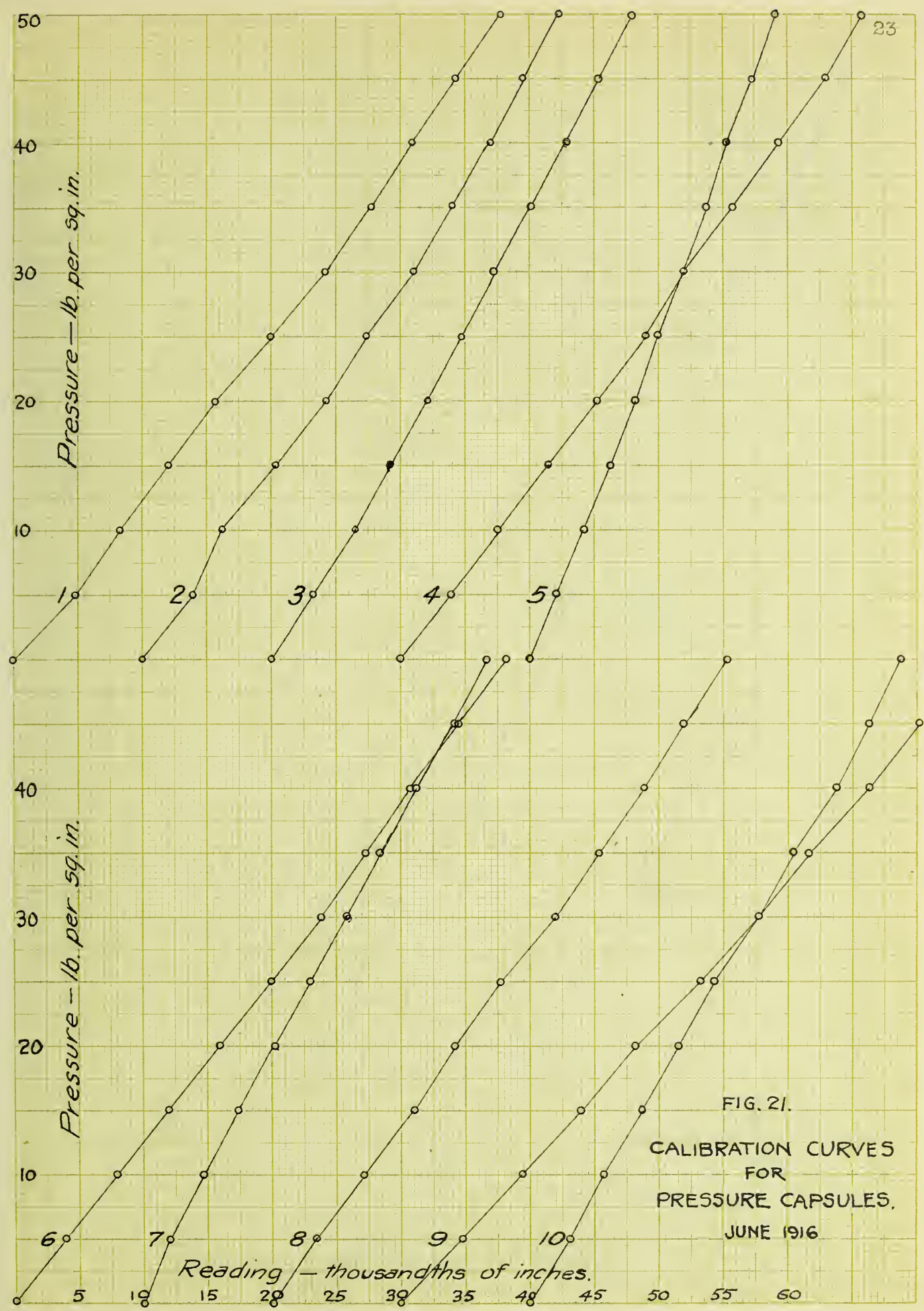


FIG. 21.
CALIBRATION CURVES
FOR
PRESSURE CAPSULES.
JUNE 1916

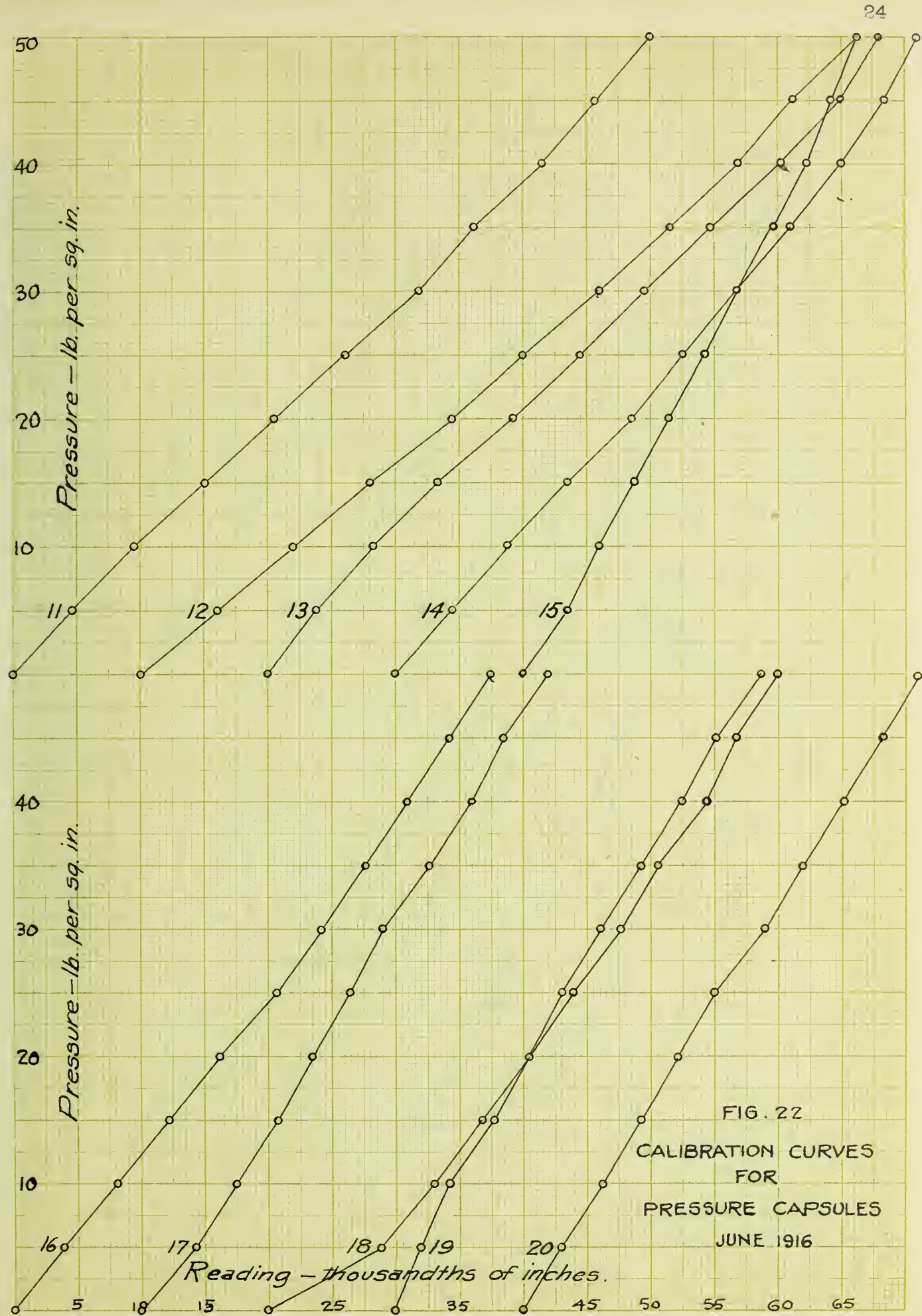


FIG. 22
CALIBRATION CURVES
FOR
PRESSURE CAPSULES
JUNE 1916

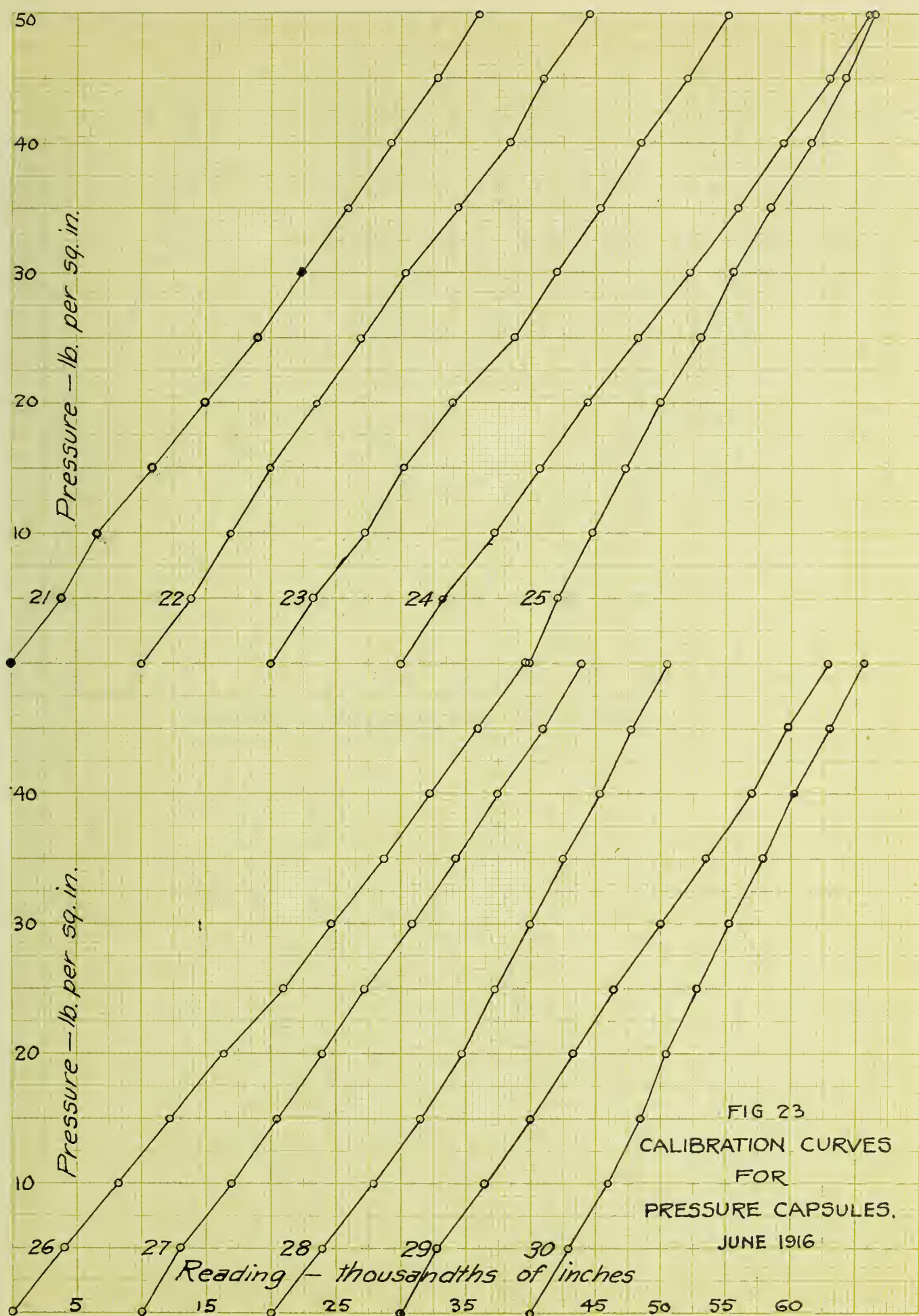


FIG 23
CALIBRATION CURVES
FOR
PRESSURE CAPSULES.
JUNE 1916



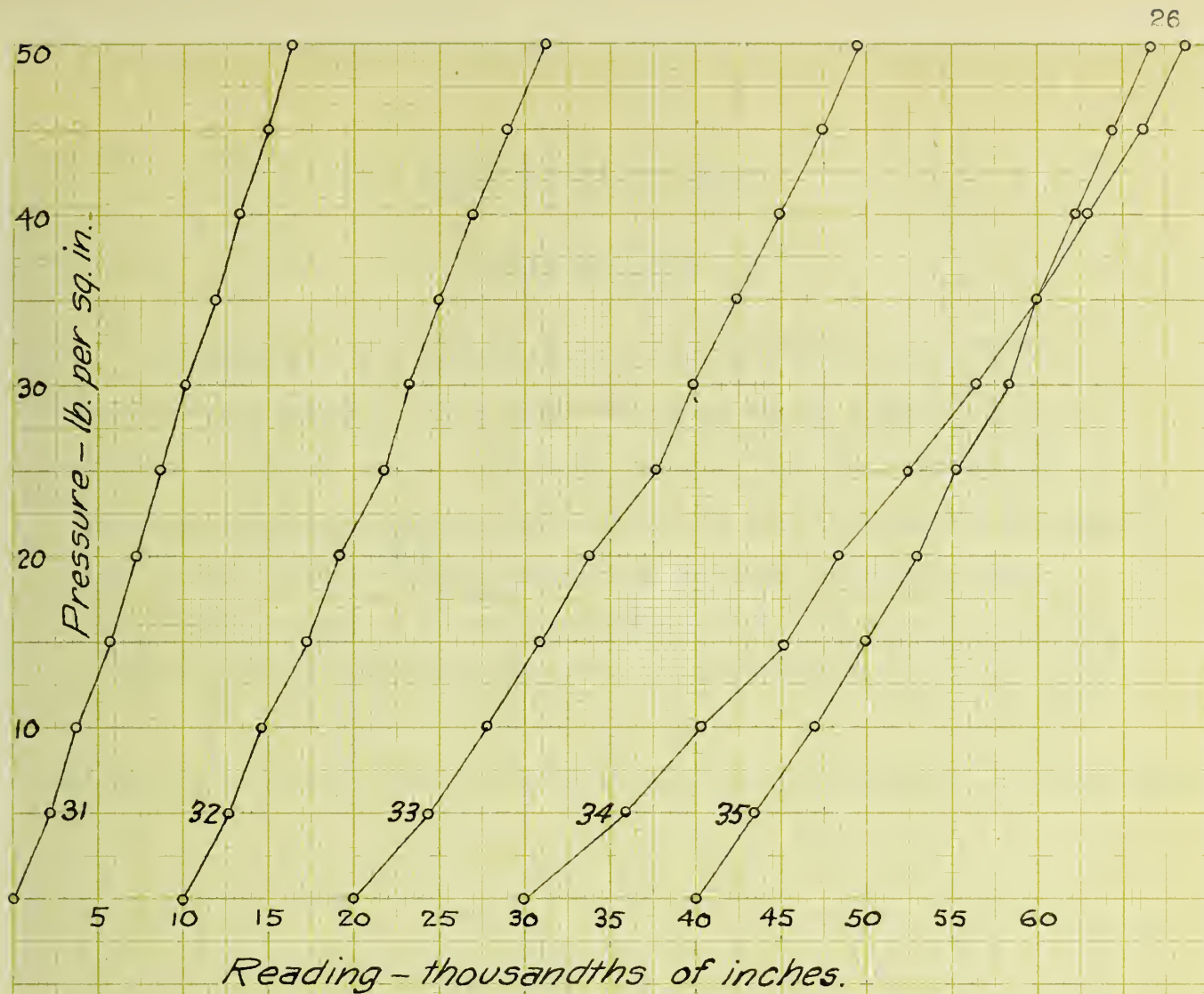
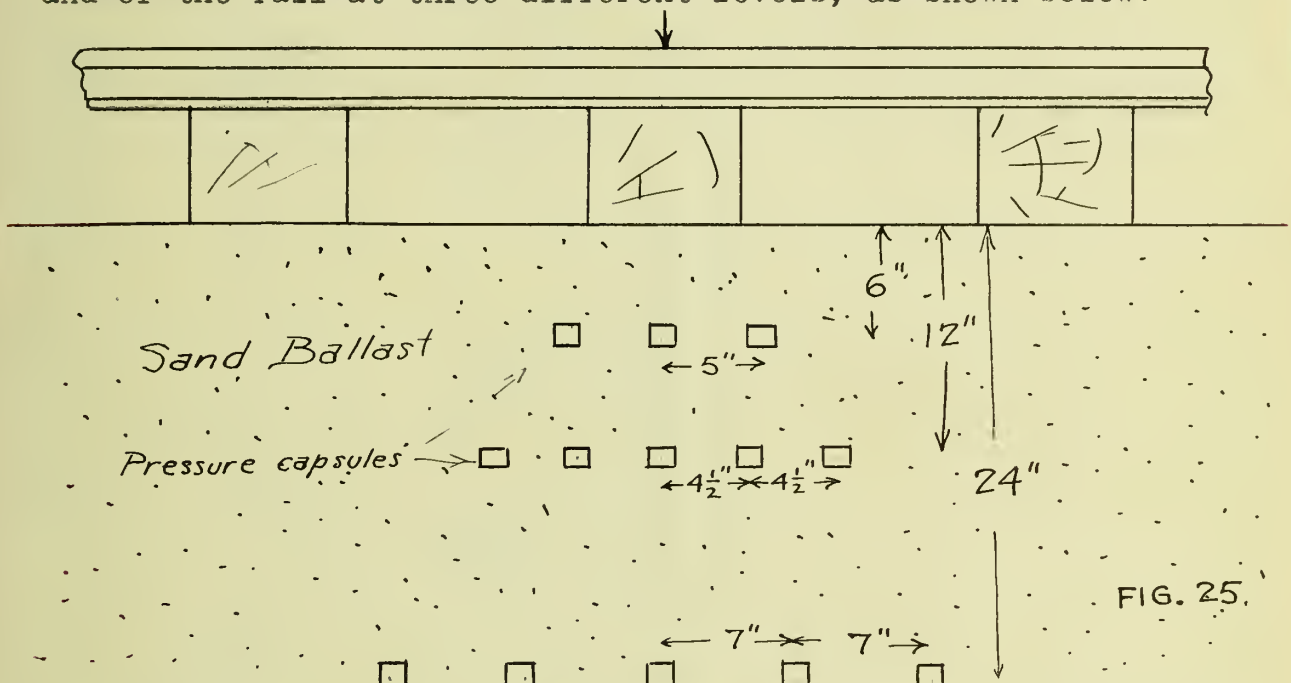


FIG 24
CALIBRATION CURVES
FOR
PRESSURE CAPSULES
JUNE 1916.

IV. DESCRIPTION OF TESTS

SAND BALLAST.

Series A. The experiments of this series were of a preliminary nature. The load was applied to a rail which rested on three ties. The sand ballast was 24 inches deep and the capsules were placed below the center line of the track and of the rail at three different levels, as shown below.



This is the only series in which the capsules were used simultaneously at different distances below the bottom the the tie. It was found that in order to get the distribution of pressure at any level in the ballast it was necessary to measure the pressure at as many points as possible. It was therefore found best to use all of the capsules at one level. It was also thought that the pipes connected to the pressure capsules might have some effect upon the distribution of pressure below.

A few of the results from this series is shown in Fig. 30

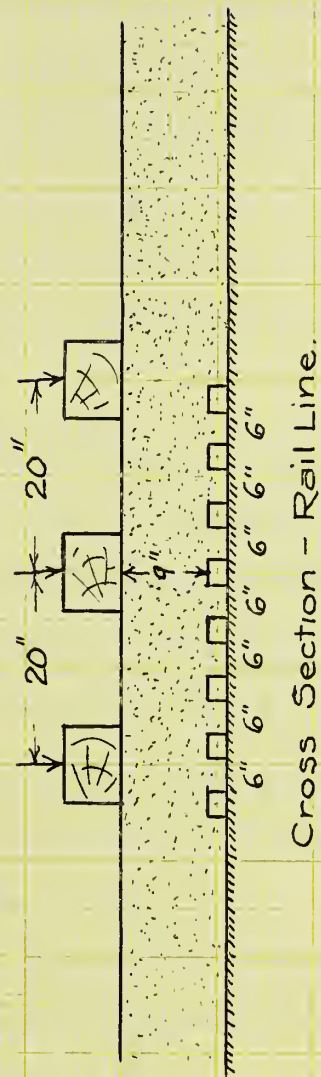
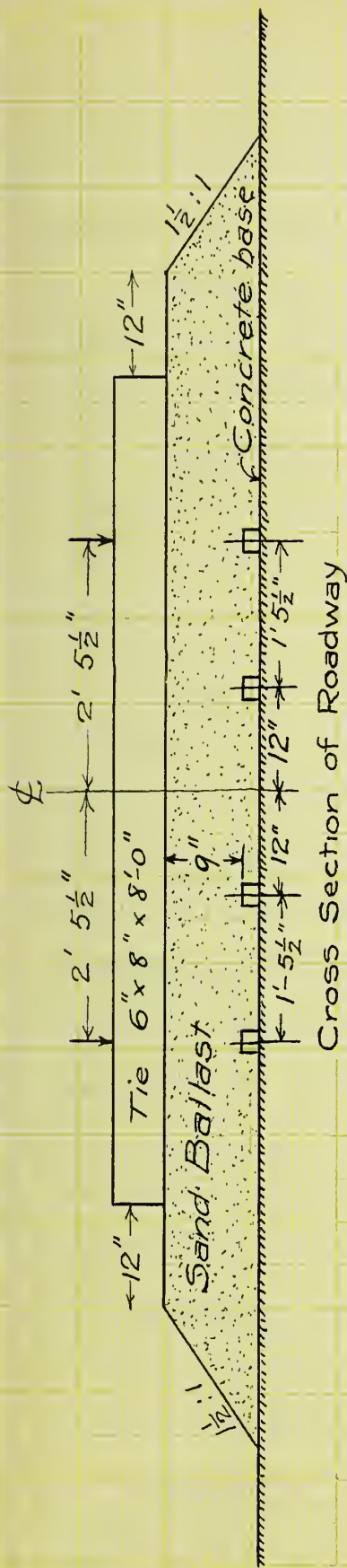


FIG. 26
ARRANGEMENT OF APPARATUS
SERIES C, D, E, F & G.

The very marked effect of pounding the ties while they are carrying load is of particular interest. It must of course be remembered that the ballast was very loose and that the loading is quite heavy.

Series B_I. Sand ballast 6 inches deep. The loads applied was limited by the capacity of some of the capsules. The results of the experiments are shown in Fig. 31.

Series B_{II} Same as B_I except that some of the capsules had to be taken out and recalibrated after Series B_I had been run. Somewhat greater loads were carried. Results are shown in Fig. 32.

Series C. Sand ballast 9 inches deep. Load applied to a single tie. Great care was taken in building up the sand to the level of this series of experiments, in order that it would be equally compacted in different parts of the mass. About six loadings were applied to compact the ballast before readings were taken. Distribution of capsules was changed for this series. The arrangement of the capsules and the results of the tests are shown in Fig. 33.

Series D. Sand ballast 9 inches deep. Equal loads applied to three ties, 20 inches center to center. See Fig. 27 The results are given in Fig. 34.

Series E. Sand ballast 9 inches deep. Three ties, 20 inches center to center. Middle tie carrying twice as much load as outside ties. Results are shown in Fig. 35.

Series F. Sand ballast 9 inches deep. Three ties, 20 inches center to center. Middle tie carrying half as much load as each outside tie. Results are shown in Fig. 36.

Series G. Sand ballast 9 inches deep. Three ties, 20 inches center to center. Middle tie carrying no load. The results of the tests in this series are shown in Fig. 37. After the level of the sand had been established in Series C no change, except in the manner of loading, was made in the ballast, or in the capsules.

Series H. Sand ballast 18 inches deep. Three ties, 20 inches center to center, equally loaded. The same arrangement of capsules was used as in the experiments with the 9 inch depth of ballast. The sand was loosened up and more was placed on until the surface of the sand was 18.5 inches above the tops of the capsules. The surface was then leveled carefully and the ties were carefully placed. The additional 1/2 inch was put on to allow for settlement. A half dozen loads were applied in each series of experiments at this depth to compact the ballast before readings were taken. The results of this series ~~is~~ ^{are} shown in Fig. 38.

Series I. Sand ballast 18 inches deep. Three ties, 20 inches center to center. Middle tie carrying twice as much load as either of the outside ties. Results of the experiments shown in Fig. 39.

Series J. Sand ballast, 18 inches deep. Three ties, 20 inches center to center. Middle tie carrying one-half the load carried on each of the outside ties. The results of this series of experiments is shown in Fig. 40.

Series K. Sand ballast, 18 inches deep. Three ties, 20 inches center to center. Middle tie carrying no load. Results of the experiments shown in Fig. 41.

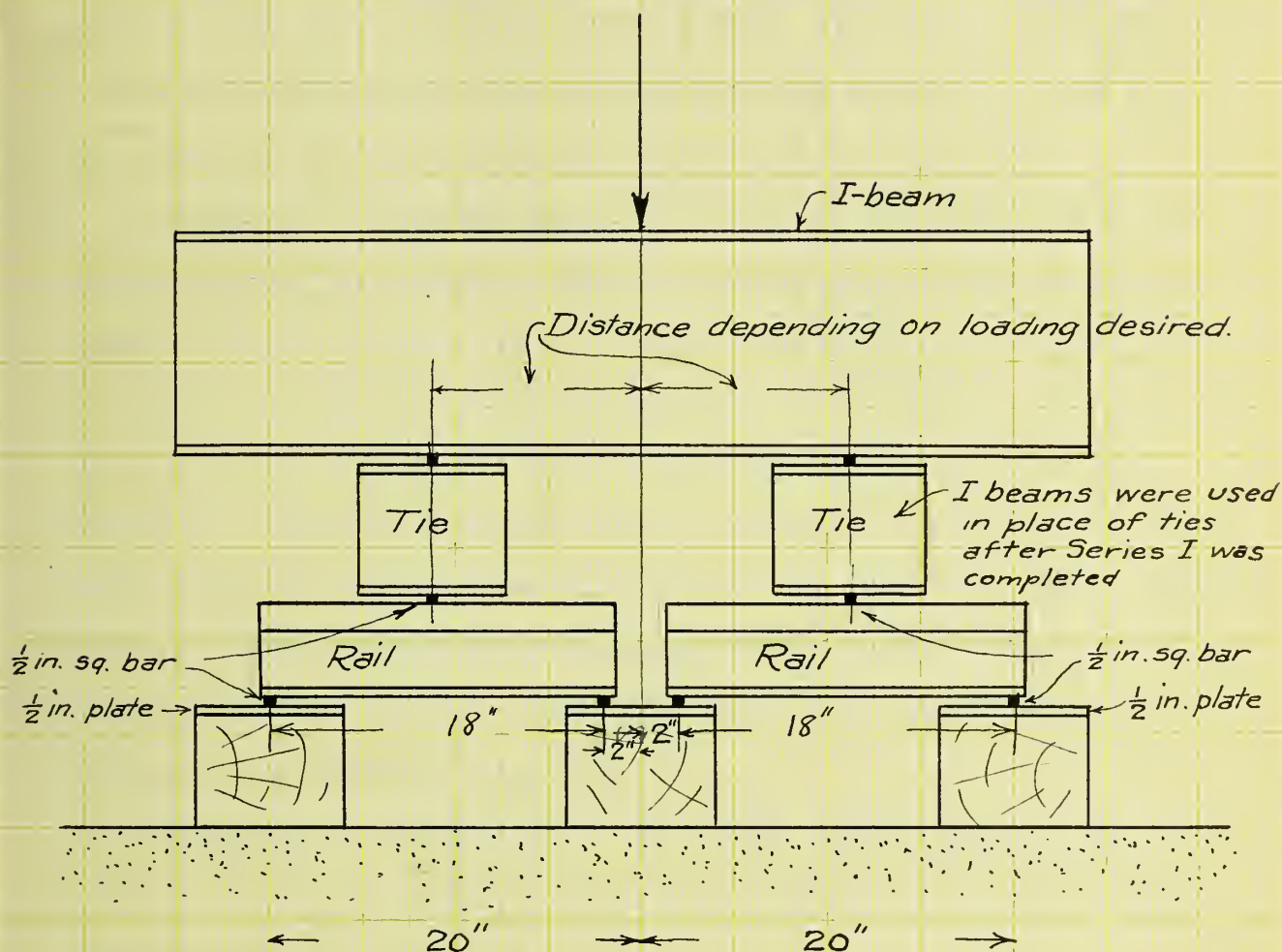


FIG. 27

Arrangement of Apparatus for Loading Three Ties.
Series H, I, J, K.

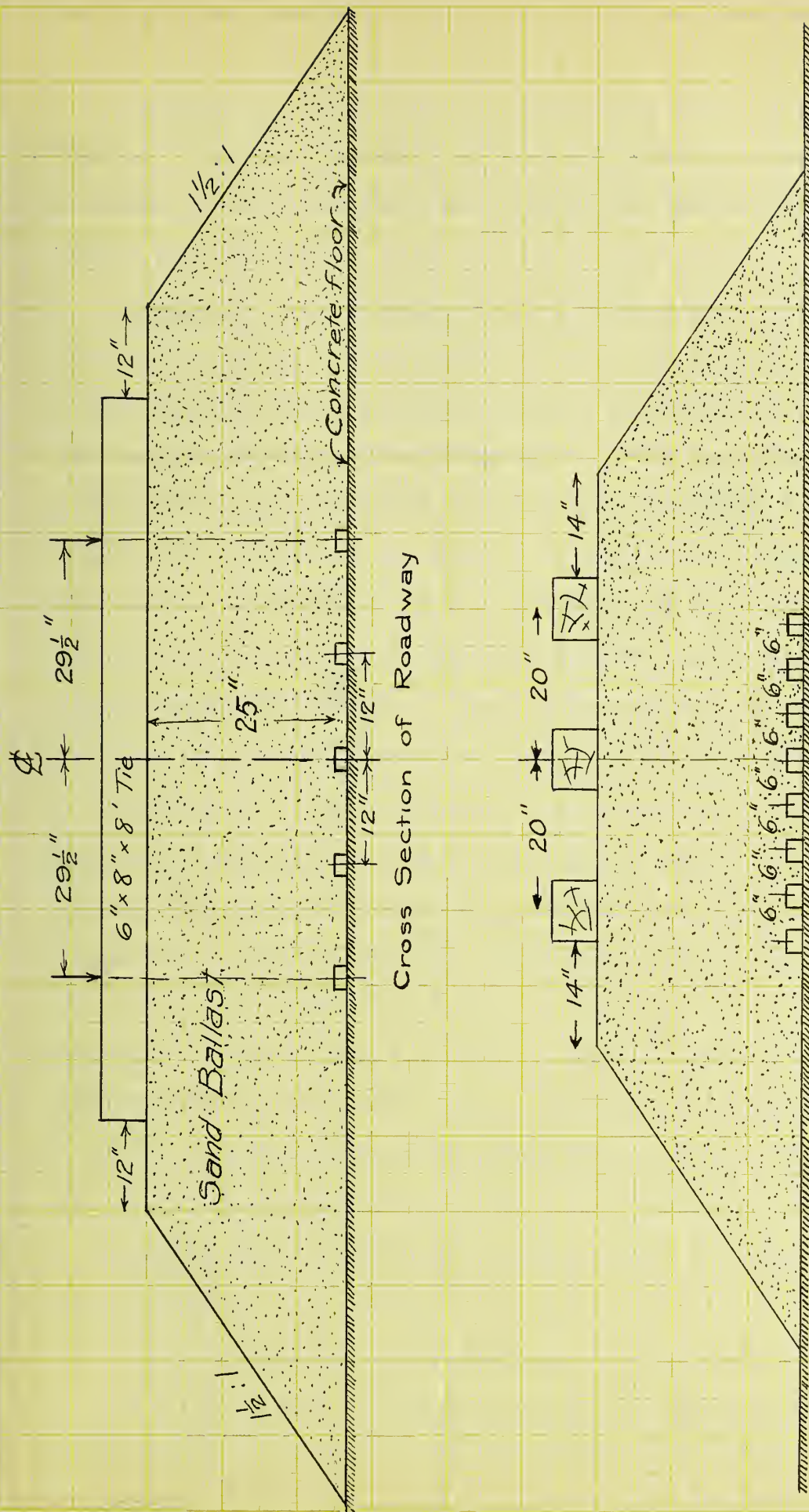
Series L. Sand ballast, 18 inches deep. Single tie loaded. The sand or the ties were not disturbed after making the tests of Series K. The only change was that only the middle tie was loaded. The sand support of the middle tie broke down under a load of 27,750 pounds, about 36.2 lb. per sq. in. on the tie. The results of the experiments are shown in Fig. 42

Series M. Sand ballast, 25 inches deep. Three ties, 20 inches center to center. Middle tie carrying twice as much load as either outside tie. After completing the experiments of Series L, the sand was loosed and sand was added until the top could be leveled off 25.5 inches above the tops of the capsules. Extreme care was used in placing the ties. In the tests with the 25 inch depth, as with the preceding tests, six loadings were applied in each case before beginning to take the readings of any series. The results of the experiments of Series M are shown in Fig. 43.

Series N. Sand ballast, 25 inches deep. Three ties, 20 inches center to center, and equally loaded. The results of the experiments are shown in Fig. 44.

Series O. Sand ballast, 25 inches deep. Three ties, 20 inches center to center. Each of the outside ties carrying twice as much load as the middle tie. Results of the experiments are shown in Fig. 45.

Series P. Sand ballast, 25 inches deep. Three ties, 20 inches center to center. Middle tie carrying no load, outside ties equally loaded. The sand broke down under a load of about 39,000 pounds. The results of the experiments are shown in Fig. 46.



Cross Section - Rail Line

FIG. 28.

SERIES M,N,O,P & Q

Series Q. Sand ballast, 25 inches deep. Single tie loaded. The sand supporting the tie broke down under a load of about 17,300 pounds. The results of the experiments are shown in Fig. 47.

Series R. Sand ballast, 12 inches deep. Single tie loaded. After completing Series Q the ballast was removed from the slab, and the capsules given a new arrangement. Fig. 137 is a photograph showing the arrangement of the capsules. Sand was then placed and carefully leveled off, allowing 1/4 inch for settlement. The tie was placed carefully on the surface of the sand. After applying a few loads the tie was raised and shovel tamped, and then load was applied up to the "yield point" which was 22,300 pounds. The test was then started. The results of the experiments of this series are shown in Fig. 48

Series S. Sand ballast, 12 inches deep. Single tie loaded. The arrangement of Series R was changed by making the surface of the sand ballast flush with the top of the tie. The sand was tamped well around the tie. Load was then applied. The limit of the capacity of several of the capsules was reached at a load of 40,500 pounds. That this was near the "yield point" of the ballast was shown by the fact that load indicated by the calibrated spring decreased about 2000 pounds in ten minutes. The experiments were then begun. The results are shown in Fig. 49.

Series T1, T2, T3, T4 and T5. Sand 12 inches deep, single tie loaded.

(T1) Series T1 is a repetition of Series S., Fig. 50.

(T2) Each end of the tie was given 50 blows with a sledge while carrying a load of 21,000 pounds. In order to make the

blows uniform, the sledge was raised 1 1/2 feet and allowed to fall. Results of the tests are shown in Fig. 51.

(T3) Sand was shoveled away from the sides of the tie.
of the tests
The results are shown in Fig. 52.

(T4) The top of the sand ballast was made 3 inches below the top of the tie and tamped with a shovel. Results of the tests are shown in Fig. 53

(T5) Sand was shoveled away until the top surface of the sand was level with the bottom of the tie, and then tamped around tie with a shovel. The results are shown in Fig. 54.

Series V. Sand ballast, 12 inches deep. Single wedge-bottom tie. The sand was loosened up thoroughly and then carefully leveled before placing the tie. The tie had a V-shaped bottom made by nailing triangular strips to the bottom of a tie. The tie was sawed back and forth to get it to an even bearing, and it was then carefully tamped. The load was limited by the yielding of the sand. The results of the tests are shown in Fig. 55.

Series W. Sand ballast, 12 inches deep. Single wedge-bottom tie. The set-up was the same as in the preceding series, except that the sand was made level with the top of the tie, and tamped. Load was then applied until the limit of the capacity of several of the capsules had been reached. The load was 44,400 pounds and there was no sign of yielding of the ballast at this load. The results of the tests are shown in Fig. 56.

ROCK BALLAST

Series X. Rock ballast, 12 inches deep. Single tie.

The capsules were all recalibrated before beginning this series of experiments. Fifteen inches of sand was placed on the concrete slab and covered with burlap. The pressure capsules were placed on top of the burlap. The arrangement of the capsules and the results of the experiments are shown in Fig. 57. In Fig. 138 is shown a photograph of the capsules before the rock ballast was placed. Considerable trouble was encountered in the experiments due to the pipes pulling out of the capsules. The maximum load was determined by the capacity of some of the capsules.

Series Y. Rock ballast, 12 inches deep. Single tie.

The conditions were the same as in Series X, except that the ballast was tamped 18 inches each side of the rail. Three loads were applied before taking readings. The results of the tests are given in Fig. 58.

Series Z. Rock ballast, 12 inches deep. Three ties, 18 inches center to center. Ties were loaded equally. A new set of oak ties were used in this series. They were of the same size as the old ones (6" x 8" x 8' 0"), but being in good condition were probably stiffer. The results of the experiments are shown in Fig. 59.

Series AA. Rock ballast, 12 inches deep. Three ties, 18 inches center to center. Ties were loaded equally. The conditions in this series similar to the preceeding series, except that the ballast was tamped 18 inches each side of the rail. The results of the experiments of this series are shown

in Fig. 60. An examination of the results of the experiments of Series Z and AA shows that the effect of tamping is to decrease the pressure below the center of the tie and to increase the pressure between rails. That is, tamping gives a better distribution of the pressure on the sub-grade.

Series AB. Rock ballast, 12 inches deep. Single tie. This series is a repetition of the experiments in Series X. The distribution of the pressure is somewhat different, due to the tamping and to the change in the positions of the parts of the ballast. The rock used in these experiments was quite large, hence a "chain of ballast" carrying the pressure from the tie to a capsule had only a few "links". A slight change in the arrangement of the ballast can therefore produce considerable changes in the pressure transmitted to any given point on the sub-grade. The results of the experiments of this series is shown in Fig. 61.

Series AC. Rock ballast, 12 inches deep. Single tie, 6" x 10" x 8' 0", with the ten-inch edge horizontal. In other respects the conditions were the same as in the preceding series. The results of the experiments of this series is shown in Fig. 62.

Series AD. Rock ballast, 12 inches deep. Single tie, 6" x 8" x 8' 0", with the six-inch face horizontal. In other respects the conditions are the same as in the two preceding series. The results of the tests are shown in Fig. 63.

Series AE. Rock ballast, 18 inches deep. Three ties, 18 inches center to center. Ties equally loaded. Ballast was placed on the pile used in the preceding experiments and

leveled off carefully, making the top surface about 18.5 inches above the top of the capsules. The additional half inch was the allowance for settling. Several loads were applied before taking readings. The maximum load in this series was determined by the capacity of the jack. The results of the experiments are shown in Fig. 64.

Series AF. Rock ballast, 18 inches deep. Single tie loaded. The maximum load was determined by the capacity of some of the capsules, and was probably a little beyond the yield point of the ballast. The results of the experiments are shown in Fig. 65.

GRAVEL BALLAST.

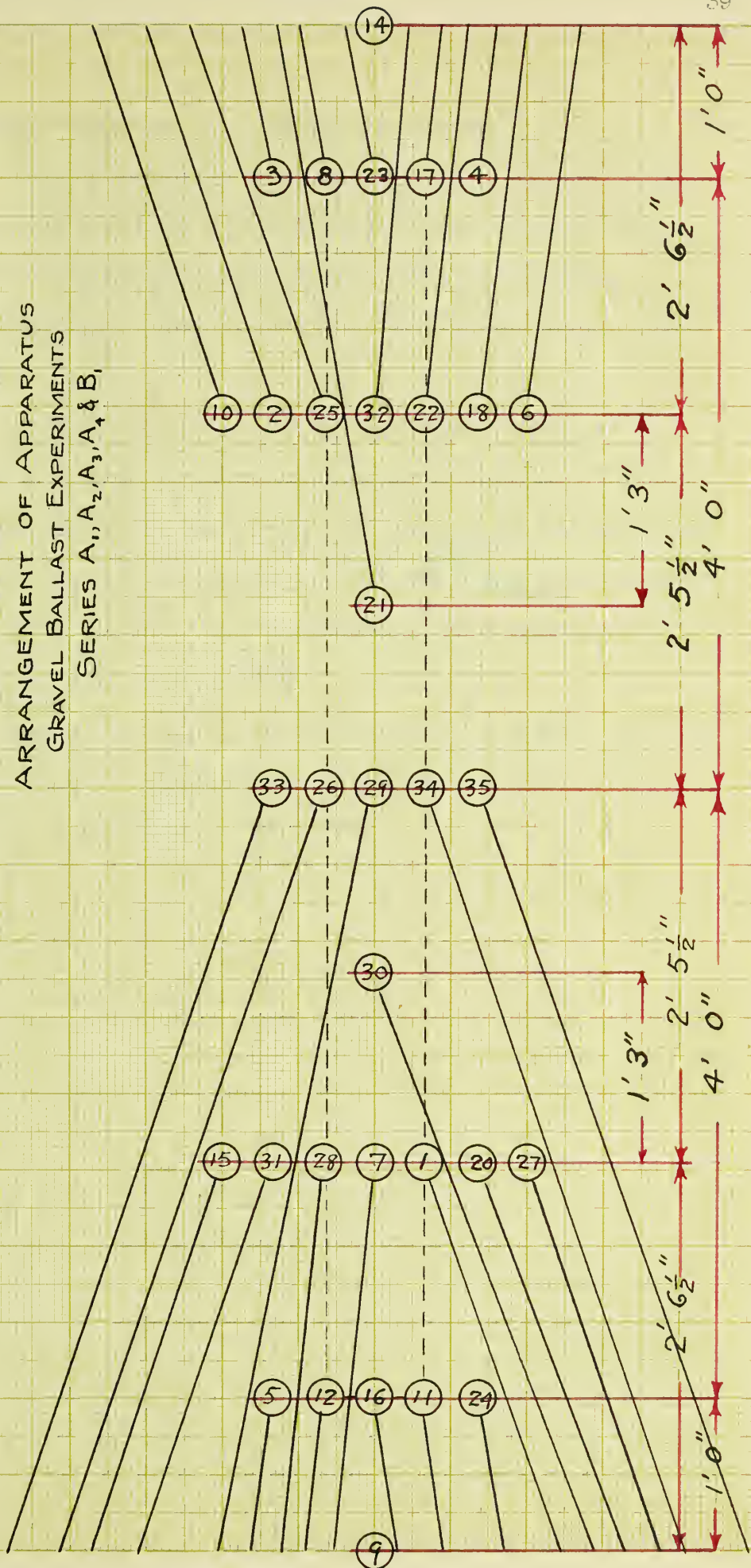
Series A₁ Gravel ballast, 12 inches deep. Single tie. All of the pressure capsules were recalibrated before placing them for the experiments on gravel ballast. A cushion of sand was used in the same manner as in the experiments with rock ballast. The depth of the sand cushion was 15 inches. The arrangement of the capsules was changed somewhat, as is shown in Fig. 29. The pipes of the pressure capsules were protected by inserting them in 1/2 inch pipe. The protecting pipes are clearly shown in some of the photographs. The results of the experiments are shown in Fig. 66

Series A₂. Gravel ballast, 12 inches deep. Single tie. Conditions the same as in the preceding series, except that the ballast was tamped. The results of the tests are shown in Fig. 67. The distribution of the pressure was not much



FIG 29

ARRANGEMENT OF APPARATUS GRAVEL BALLAST EXPERIMENTS SERIES A₁, A₂, A₃, A₄ & B₁



different from that found in the preceding series.

Series A₃. Gravel ballast, 12 inches deep. Single wedge bottom tie. The wedge bottom tie was used in place of the ordinary tie of the preceding experiments, and carefully tamped to a firm bearing. The results of the experiments are shown in Fig. 68.

Series A₄. Gravel ballast, 12 inches deep. Single tie. A 6" x 8" x 8' 0" tie with capsules embedded in order that the pressure on the tie might be measured was used. The arrangement of the capsules in the tie is shown in Fig. 69, and the results of the tests are also shown. The pressure on the capsules 12 inches below is shown in Fig. ⁷⁰69.

Series B₁. Gravel ballast, 12 inches deep. Three ties, 18 inches center to center. The ties were loaded equally. The results of the test are shown in Fig. 70.

Data from the Tests. Such a large amount of data has been accumulated that it will not be included in this thesis. All of the data for Series A₂ (single tie on 12 inches of gravel ballast) has been included to illustrate the method of recording the data and of working it up.

The readings of the dynamometer and of the pressure capsules were recorded on a special printed data sheet. Three sets of readings were taken in Series A₂. The readings for the same load are averaged at the bottom of the page. From the average readings, the pressures on the capsules are determined from the calibration curves of the capsules. A summary was then prepared from which the average increase in pressure at different distances from the center line of the tie is obtained for the end line capsules, for the rail line capsules, and for the capsules below the center line of the track.

Fig. 67 is a plan view of the tie and of the capsules. The average values obtained as explained above are plotted. The increase in the pressure on each capsule due to the 19,600 and to the 13,600 pound loads are written above and below the capsule respectively. The pressures due to the higher load are in red.

In this manner it is possible to represent the results of the tests in a very compact and useable form.

TESTS OF BALLAST

JOINT COMMITTEE ON STRESSES IN RAILROAD TRACK

Kind of Ballast Gravel
 Condition Dry
 Depth Under Tie 12 in.
 Loading 0 - 100 - 0
 Sand bed 15 in. deep

No. Ties 1
 Spacing 8 ft
 Bearing Area 784 sq. in.

Recorder A.R.
 Observers B.R.O.

Series A₂
 Date 8/23/16

Dynamometer			PRESSURE CAPSULE READINGS																							
Rdg. No.	Load On	Rdg. Off	No. 6		No. 18		No. 4		No. 22		No. 17		No. 32		No. 14		No. 23		No. 8		No. 21		No. 3			
			Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.		
1	0	0	1.8		0.8		0.9		0.8		2.9		0.9		2.2		2.0		1.0		3.1		1.4			
2	6700	40	2.3		2.4		1.8		5.5		4.6		4.6		2.4		5.1		2.9		8.1		2.5			
3	13600	80	2.6		3.9		2.2		10.3		6.9		8.3		2.5		8.5		4.9		14.0		3.1			
4	19600	110	2.8		5.0		2.7		18.9		9.4		11.8		2.7		11.5		7.0		20.2		3.6			
5		50	2.0	8400	2.4		1.6		11.7		7.0		6.0		2.2		7.2		3.5		15.8		2.6			
6	0	0	1.4	0	0.8		0.8		0.7		2.9		1.2		2.0		1.8		0.6		3.2		1.3			
7	6700	40	2.0		2.1		1.6		4.9		4.5		4.7		2.3		4.6		2.2		9.2		2.4			
8	13600	80	2.5		3.8		2.2		11.0		7.2		7.9		2.5		8.0		4.4		14.6		3.1			
9	19600	110	2.7		5.0		2.6		17.9		9.6		11.2		2.4		11.3		6.6		19.6		3.5			
10		50	1.9	8400	2.2		1.6		11.8		7.1		6.7		2.2		7.2		3.1		15.1		2.4			
11	0	0	1.4	0	0.8		0.9		0.8		2.8		0.8		2.2		1.8		0.6		3.2		1.6			
12	6700	40	2.0		2.2		1.3		5.2		4.4		4.3		2.3		5.4		2.2		9.4		2.4			
13	13600	80	2.4		3.9		2.1		10.4		7.2		7.7		2.4		8.2		4.7		14.6		3.1			
14	19600	110	2.7		5.1		2.6		17.2		9.5		11.0		2.6		11.6		6.9		19.2		3.5			
15		50	1.7	8400	2.3		1.6		11.1		6.8		6.8		2.1		7.2		3.5		15.0		2.2			
16	0	0	1.2	0	0.6		0.8		0.5		2.5		0.8		2.0		1.4		0.6		2.9		0.8			
									Averages																	
1'	0	0	1.4	1.9	0.8	1.0	0.8	1.1	0.7	0.9	2.8	5.0	1.0	2.0	2.1	2.6	1.8	2.8	0.7	1.3	3.1	4.1	1.4	2.2		
2'	6700	40	2.1	2.7	2.2	2.9	1.6	2.2	5.2	10.0	4.5	8.4	4.5	9.0	2.3	2.8	5.0	7.8	2.4	3.2	8.9	13.5	2.4	3.7		
3'	13600	80	2.5	3.2	3.9	5.0	2.2	2.8	10.6	16.2	7.1	11.1	8.0	16.4	2.5	3.2	8.2	12.3	4.7	7.7	14.4	19.3	3.1	4.9		
4'	19600	110	2.7	3.7	5.0	6.5	2.6	3.5	18.0	26.6	9.5	14.3	11.3	24.3	2.6	3.3	11.5	17.0	6.8	9.4	19.7	26.3	3.5	5.4		
5'		50	1.9	2.5	2.3	3.0	1.6	2.2	11.5	17.0	7.0	11.3	6.5	13.0	2.2	2.7	7.2	10.8	3.4	4.8	15.3	20.6	2.4	3.7		
6'	0	0	1.4	1.9	0.8	1.0	0.8	1.1	0.7	0.9	2.8	5.0	1.0	2.0	2.1	2.6	1.8	2.8	0.7	1.3	3.1	4.1	1.4	2.2		

JOINT COMMITTEE ON STRESSES IN RAILROAD TRACK

Kind of Ballast Grave! --
Condition -- Dry
Depth Under Tie 12 in.
Loading 0-100-0
Sand bed 15 in. deep

No. Ties 1
Spacing —
Length 8 ft
Bearing Area 78

Recorder A.R.
Observers B.R.O.

Series A₂
Date 8/23/16

Dynamometer			PRESSURE CAPSULE READINGS															
Rdg. No.	Load On	Rdg. Off	No. 25 Rdg.	No. 2 Rdg.	No. 10 Rdg.	No. 33 Rdg.	No. 26 Rdg.	No. 15 Rdg.	No. 31 Rdg.	No. 29 Rdg.	No. 5 Rdg.	No. 28 Rdg.	No. 12 Rdg.					
1	0	0	2.2	0.6	0.8	1.6	2.4	0.9	0.6	2.1	1.0	1.6	3.1					
2	6700	40	3.2	2.4	1.1	2.7	10.3	1.3	1.5	6.0	1.3	5.8	5.4					
3	13600	80	6.8	4.0	1.5	3.4	13.8	1.6	2.2	9.3	1.7	9.6	8.1					
4	19600	110	10.0	5.1	1.6	4.1	17.5	1.6	2.6	13.1	1.8	14.1	9.9					
5		50	6.1	2.5	1.2	3.2	16.2	1.0	1.1	11.5	1.4	8.9	5.9					
6	0	0	2.5	0.7	1.0	1.3	8.0	0.6	0.6	2.7	0.9	1.6	3.0					
7	6700	40	3.6	2.2	1.2	3.0	13.0	0.8	1.4	7.7	0.8	5.2	4.2					
8	13600	80	6.2	4.2	1.6	3.6	15.6	1.0	2.3	10.9	1.2	9.5	7.1					
9	19600	110	9.2	5.0	2.1	4.1	18.4	1.1	3.0	13.1	1.6	14.0	9.4					
10		50	5.9	2.3	1.2	3.1	17.4	0.8	1.6	11.4	1.0	8.6	5.7					
11	0	0	2.1	0.7	1.0	1.6	9.3	0.6	1.0	3.0	0.8	2.0	2.8					
12	6700	40	3.2	2.0	1.4	3.0	14.0	0.9	1.6	8.1	1.1	5.5	4.1					
13	19600	80	5.8	3.7	1.6	3.7	16.5	1.1	2.3	11.0	1.3	10.0	7.1					
14	19600	110	8.8	4.8	2.2	4.0	19.1	1.2	2.9	13.0	1.7	14.0	9.7					
15		50	4.9	1.8	1.6	2.6	17.8	0.8	1.5	11.1	1.0	8.5	5.6					
16	0	0	1.5	0.4	1.0	0.4	9.3	0.6	0.8	2.7	0.7	2.0	2.6					
							Averages:											
1'	0	0	2.1	5.1	0.9	1.3	5.0	6.0	0.7	2.8	4.9	1.8	2.8					
2'	6700		3.3	7.3	1.2	2.9	12.4	15.1	1.0	7.3	11.2	1.1	5.9					
3'	13600		6.3	13.6	1.6	3.6	15.3	18.5	1.2	10.4	15.7	1.4	9.7					
4'	19600		9.1	18.5	2.0	4.1	18.3	22.7	1.3	13.1	19.9	1.7	14.0					
5'		8400	5.4	11.6	1.3	3.0	17.1	20.7	0.9	11.3	17.2	1.1	8.7					
6'	0	0	2.1	5.1	0.9	1.3	5.0	6.0	0.7	2.8	4.9	1.8	2.8					

TESTS OF BALLAST

JOINT COMMITTEE ON STRESSES IN RAILROAD TRACK

Kind of Ballast Gravel
 Condition Dry
 Depth Under Tie 12 in.
 Loading 0-100-0
 Sand bed 15 in. deep.

No. Ties 1
 Spacing 8 ft.
 Length 8 ft.
 Bearing Area 784 sq. in.

Recorder A.R.
 Observers B.R.O.

Series A₂
 Date 8/23/16

Dynamometer			PRESSURE CAPSULE READINGS																					
Rdg. No.	Load On	Rdg. Off	No. 7...		No. 9...		No. 16...		No. 11...		No. 24...		No. 1....		No. 30...		No. 20...		No. 27...		No. 34...		No. 35...	
			Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.	Rdg.	Pr.
1	0	0	0.9		2.0		2.1		1.9		2.0		2.2		2.3		1.1		1.0		4.9		2.6	
2	6700	40	3.9		2.2		2.9		3.6		2.4		6.3		4.9		2.8		1.8		9.4		4.1	
3	13600	80	9.5		2.1		3.9		5.3		2.9		12.3		8.7		4.2		2.3		14.2		5.4	
4	19600	110	15.1		2.2		5.0		6.1		3.4		18.0		13.0		5.2		2.8		19.5		6.5	
5		50	10.2		2.0		3.6		4.0		2.6		11.0		10.0		3.0		1.6		17.2		5.7	
6	0	0	0.6		1.8		2.2		2.1		1.8		2.0		2.2		0.9		1.1		6.4		3.0	
7	6700	40	3.7		2.2		2.6		3.1		2.2		6.0		6.0		3.0		1.8		12.7		4.7	
8	13600	80	8.9		2.2		3.9		5.0		2.8		11.6		9.4		3.7		2.4		15.5		5.8	
9	19600	110	14.1		1.8		4.9		6.7		3.1		17.3		13.0		4.9		2.9		19.6		6.7	
10		50	8.6		2.0		3.0		3.7		2.3		10.2		10.1		2.6		1.8		17.4		5.9	
11	0	0	1.1		1.8		2.0		1.7		1.8		2.0		2.3		0.9		0.9		7.4		2.9	
12	6700	40	3.9		2.0		2.5		3.0		2.3		6.0		6.3		2.9		1.6		13.3		4.8	
13	13600	80	9.2		2.0		3.6		5.0		2.9		11.9		9.8		3.6		2.3		16.8		6.0	
14	19600	110	14.4		2.0		4.5		6.6		3.3		16.9		13.0		4.7		2.8		19.5		6.8	
15		50	8.8		1.4		3.0		4.0		2.0		10.2		9.9		2.3		1.5		17.6		5.3	
16	0	0	0.8		1.3		1.8		1.9		1.4		2.1		2.6		0.9		0.7		7.0		2.8	
											Averages													
1'	0	0	0.9	1.9	1.9	1.8	2.0	2.6	1.9	1.9	1.8	1.9	2.1	0.7	2.3	2.7	0.9	1.4	0.9	1.4	6.4	5.3	2.8	4.0
2'	6700	40	3.8	7.0	2.1	2.1	2.7	3.7	3.2	3.2	2.3	2.4	6.1	2.7	5.7	7.5	2.9	4.5	1.7	2.8	11.8	11.7	4.5	6.4
3'	13600	80	9.2	15.6	2.1	2.1	3.8	4.9	5.3	5.6	2.9	3.2	11.9	7.9	9.3	16.7	3.8	6.0	2.3	3.5	15.5	16.3	5.8	8.5
4'	19600	110	14.5	24.8	1.8	1.7	4.8	6.2	6.7	7.1	3.4	3.6	17.4	14.3	13.0	25.6	4.9	7.7	2.8	4.3	19.5	21.2	6.7	9.7
5'		50	9.2	15.6	1.8	1.7	3.2	4.1	3.9	4.0	2.3	2.4	10.5	6.3	10.0	18.5	2.6	4.0	1.6	2.6	17.4	18.8	5.6	8.2
6'	0	0	0.9	1.9	1.9	1.8	2.0	2.6	1.9	1.9	1.8	1.9	2.1	0.7	2.3	2.7	0.9	1.4	0.9	1.4	6.4	5.3	2.8	4.0

Averages



Series A-2
Date 8/23/16

PRESSURE CAPSULE REASONS

4.

Summary Series A₂ CENTER LINE AND X CAPSULES.

Sheet No. 5

LOAD		Center		4 in. from Center				8 in. from Center				X and X'			
Total	lb per sq. in.	29	ΔP	26	34	Av. P	ΔP	33	35	Av P	ΔP	x	x'	ΔP	Av. P
0	0	4.9	0	6.0	5.3	5.6	0	1.6	4.0	2.8	0	2.7	4.1	3.4	0
6700	8.54	11.2	6.3	15.1	11.7	13.4	7.8	4.2	6.4	5.3	2.5	7.5	13.5	10.5	7.1
13600	17.34	15.7	10.8	18.5	16.3	17.4	11.8	5.2	8.5	6.8	4.0	16.7	19.3	18.0	14.6
19600	25.0	19.9	15.0	22.7	21.2	21.9	16.3	5.7	9.7	7.7	4.9	25.6	26.3	26.0	22.6
8400	10.72	17.2	12.3	20.7	18.8	19.7	14.1	4.2	8.2	6.2	3.4	18.5	20.6	19.6	16.2
0	0	4.9	0	6.0	5.3	5.6	0	1.6	4.0	2.8	0	2.7	4.1	3.4	0

RAIL LINE CAPSULES

Center				4 in. from Center				8 in. from Center				12 in. from Center									
32	7	Av P	ΔP	25	22	28	1	Av. P	ΔP	2	18	31	20	Av. P	ΔP	10	6	15	27	Av. P	ΔP
2.0	1.9	2.0	0	5.1	0.9	2.4	0.7	2.3	0	0.7	1.0	1.5	1.4	1.1	0	1.3	1.9	0.7	1.4	1.4	0
9.0	7.0	8.0	6.0	7.3	10.0	5.9	2.7	8.5	6.2	2.7	2.9	2.8	4.5	3.2	2.1	1.7	2.7	1.0	2.8	2.1	0.7
16.4	15.6	16.0	14.0	13.6	16.2	12.3	7.9	12.5	10.2	5.6	5.0	4.7	6.0	5.4	4.3	2.7	3.2	1.2	3.5	2.7	1.3
24.3	24.8	24.6	22.6	18.5	26.6	18.7	14.3	19.5	17.2	7.4	6.5	6.5	7.7	7.0	6.9	3.2	3.7	1.4	4.3	3.2	1.8
13.0	15.6	14.3	12.3	11.6	17.0	11.0	6.3	11.5	9.2	2.7	3.0	2.6	4.0	3.1	2.0	1.8	2.5	0.9	2.6	1.9	0.5
2.0	1.9	2.0	0	5.1	0.9	2.4	0.7	2.3	0	0.7	1.0	1.5	1.4	1.1	0	1.3	1.9	0.7	1.4	1.4	0

END LINE AND Y CAPSULES.

Center				4 in. from Center				8 in. from Center				Y and Y'								
	16	23	Av. P	ΔP	8	17	12	11	Av. P	ΔP	3	4	5	24	Av. P	ΔP	9	14	Av. P	ΔP
	2.6	2.8	2.7	0	1.3	5.0	2.3	1.9	2.8	0	2.2	1.1	1.8	1.9	1.8	0	1.8	2.6	2.2	0
	3.7	7.8	5.7	3.0	3.2	8.4	3.8	3.2	4.7	1.9	3.7	2.2	2.8	2.4	2.8	1.0	2.1	2.8	2.4	0.2
	4.9	12.3	8.6	5.9	7.7	11.1	6.1	5.6	7.6	4.8	4.9	2.8	3.3	3.2	3.6	1.8	2.1	3.2	2.6	0.4
	6.2	17.0	11.6	8.9	9.4	14.3	8.3	7.1	9.8	7.0	5.4	3.5	4.3	3.6	4.2	2.4	1.7	3.3	2.5	0.3
	4.1	10.8	7.5	4.8	4.8	11.3	4.7	4.0	6.2	3.4	3.7	2.2	2.8	2.4	2.8	1.0	1.7	2.7	2.3	0.1
	2.6	2.8	2.7	0	1.3	5.0	2.3	1.9	2.8	0	2.2	1.1	1.8	1.9	1.8	0	1.8	2.6	2.2	0

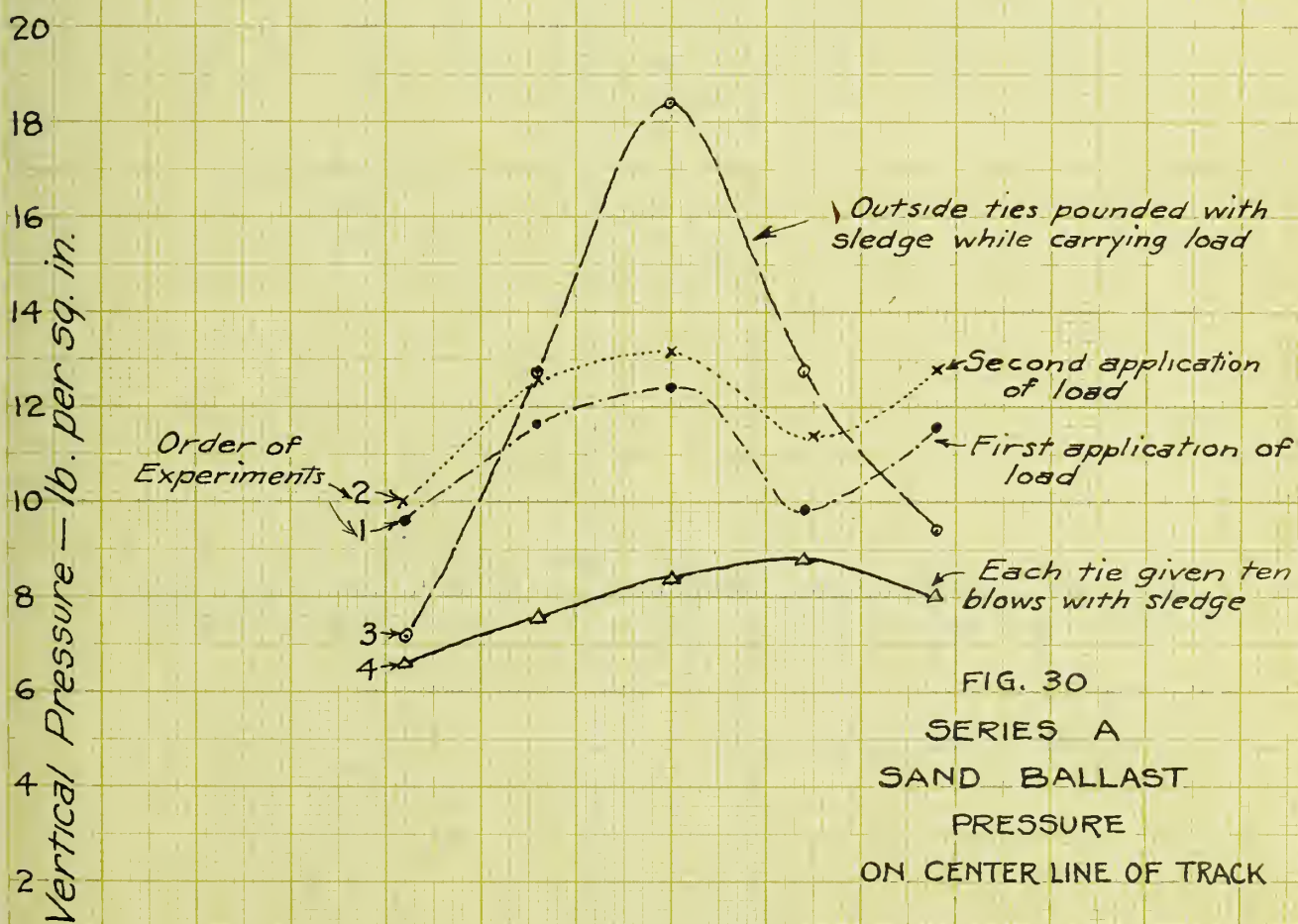
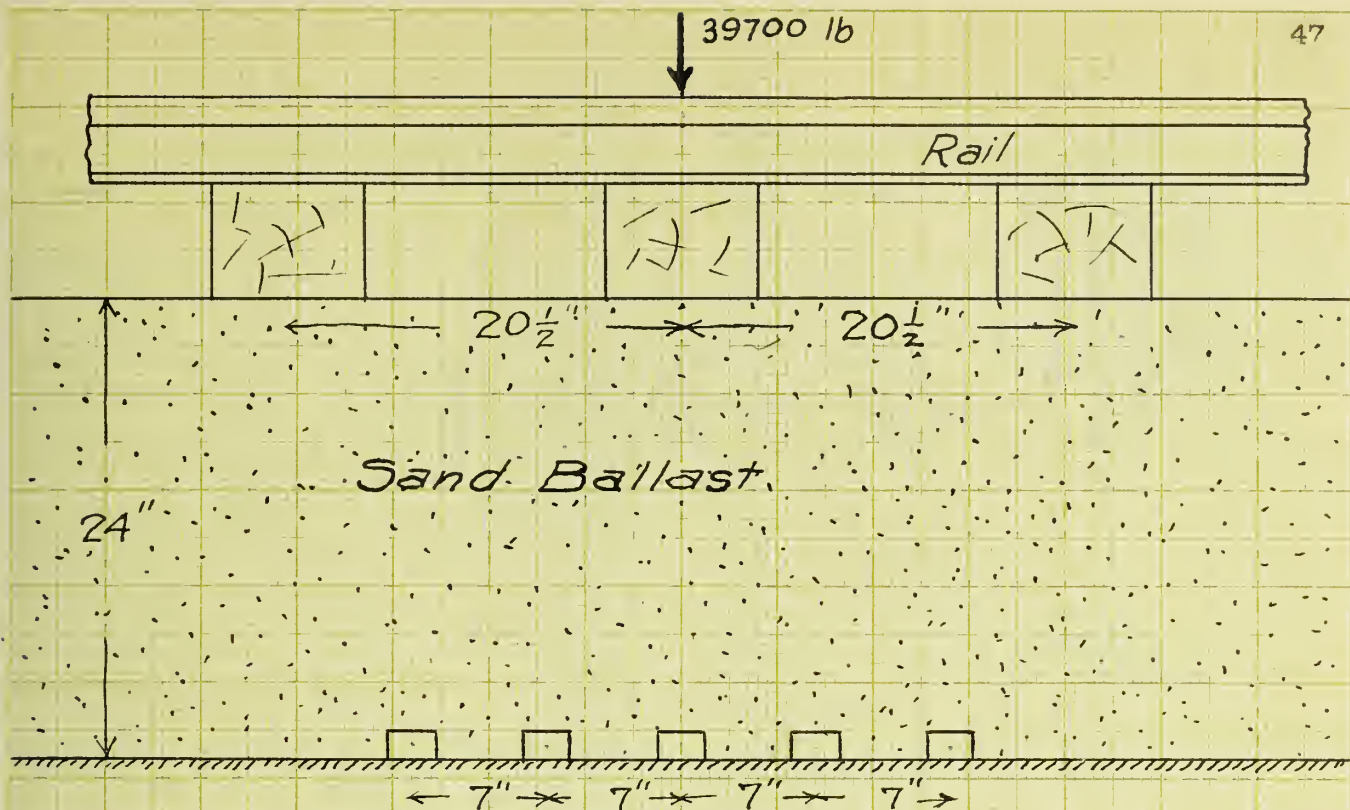


FIG. 30
 SERIES A
 SAND BALLAST
 PRESSURE
 ON CENTER LINE OF TRACK

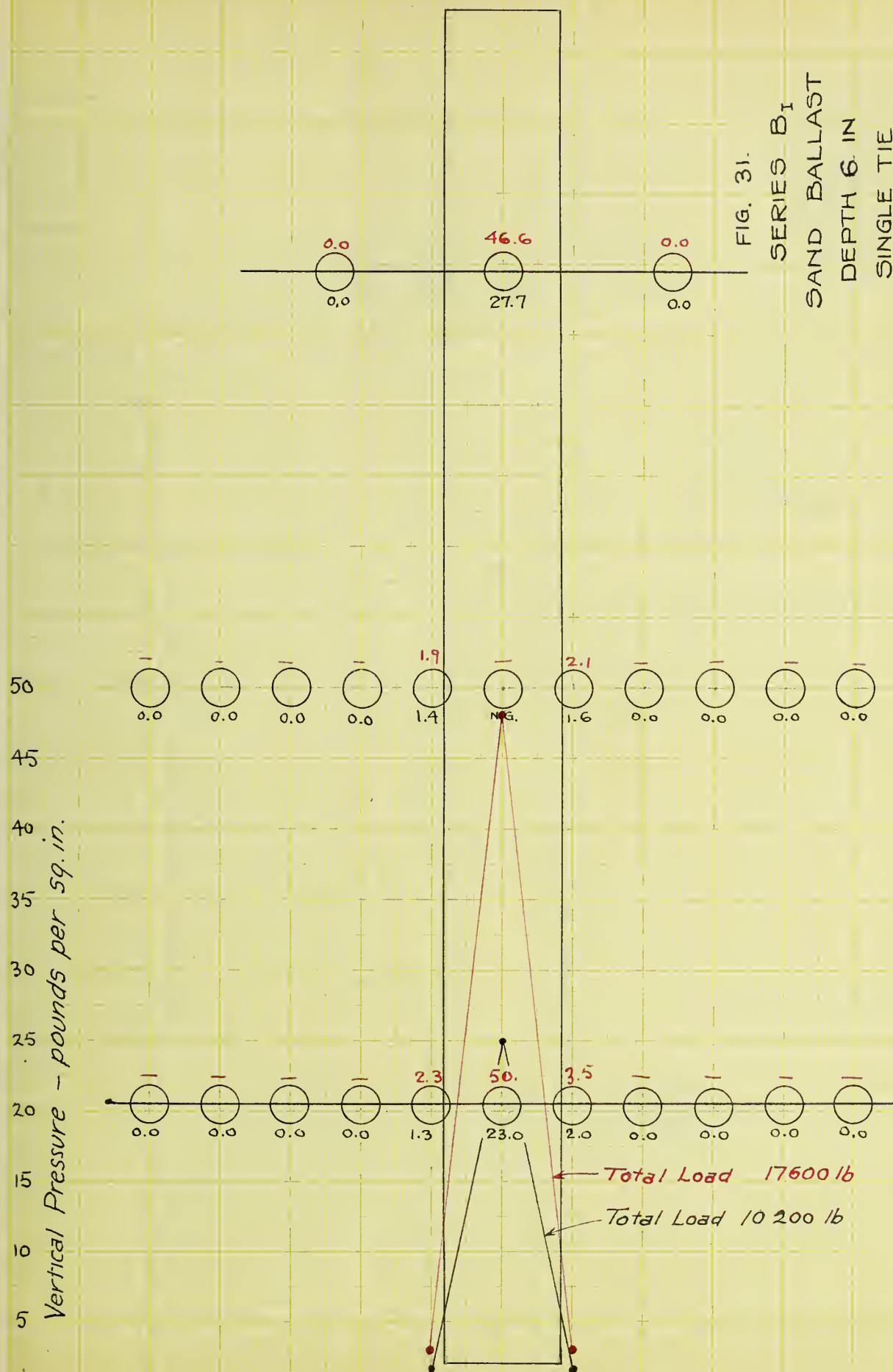
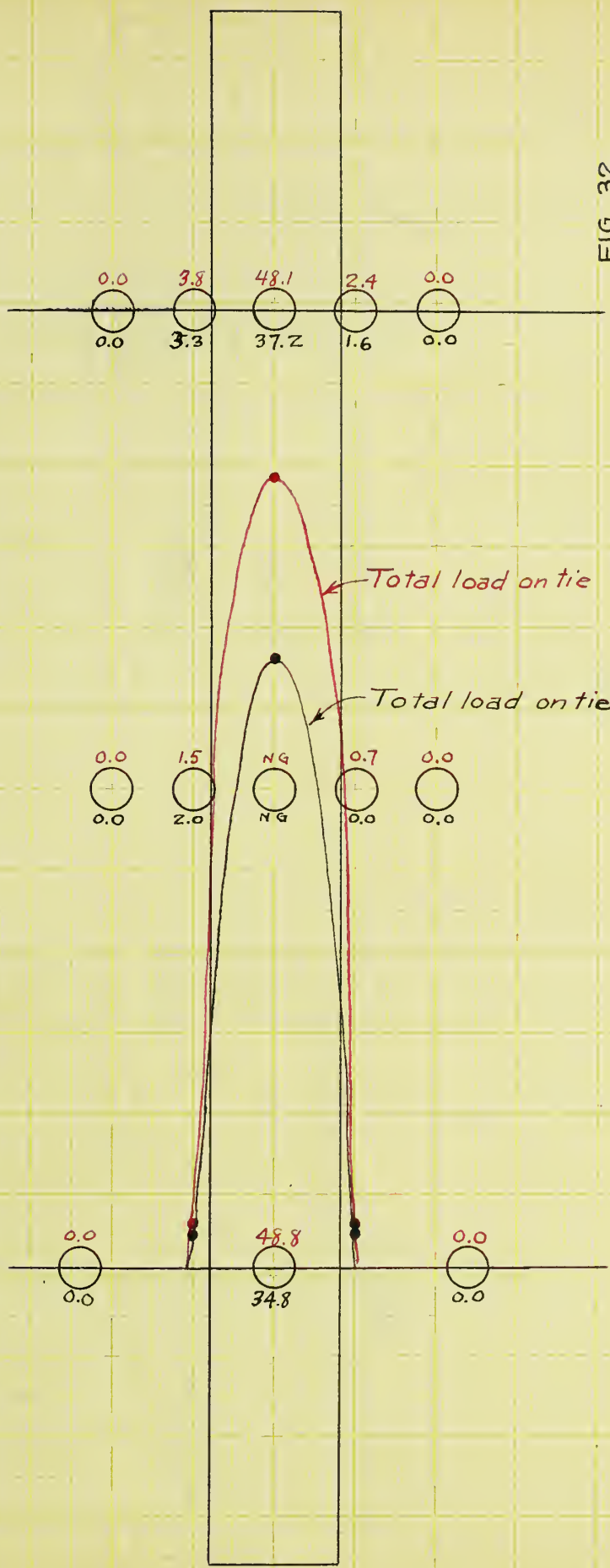


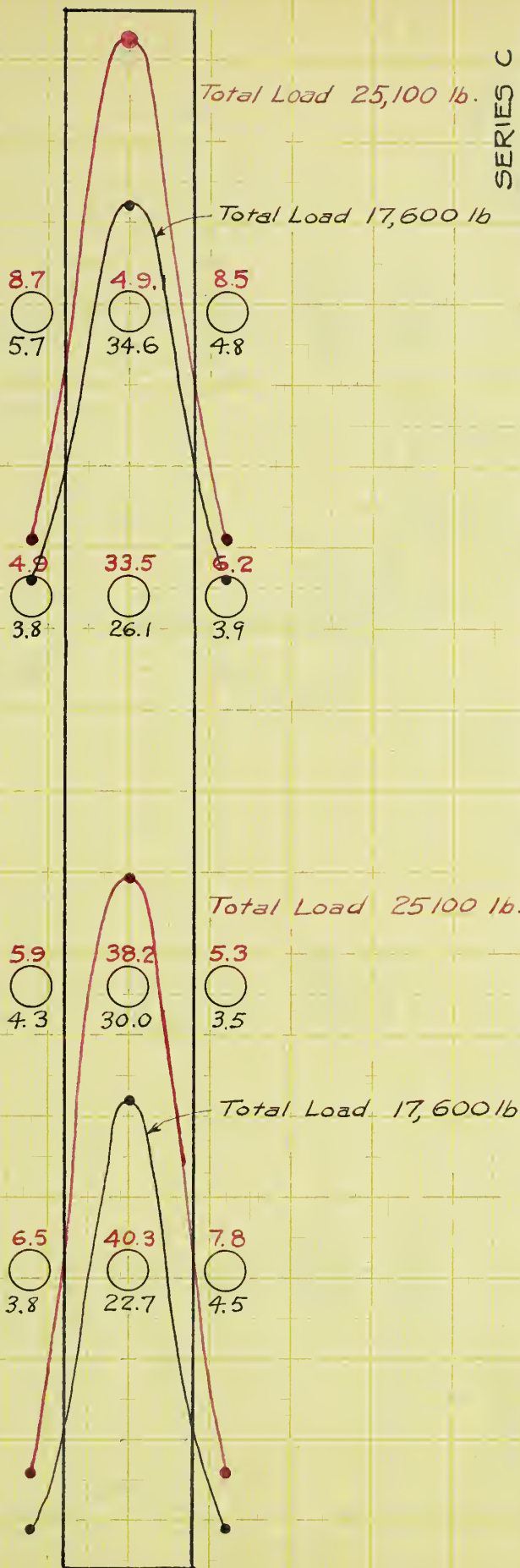
FIG. 32
 SERIES B_{II}
 SAND BALLAST
 DEPTH 6 IN.
 SINGLE TIE.

Vertical Pressure — lb. per sq. in.
 Center Line of Rail



Vertical Pressure - lb per sq. in.
12 in from C.L. of Track

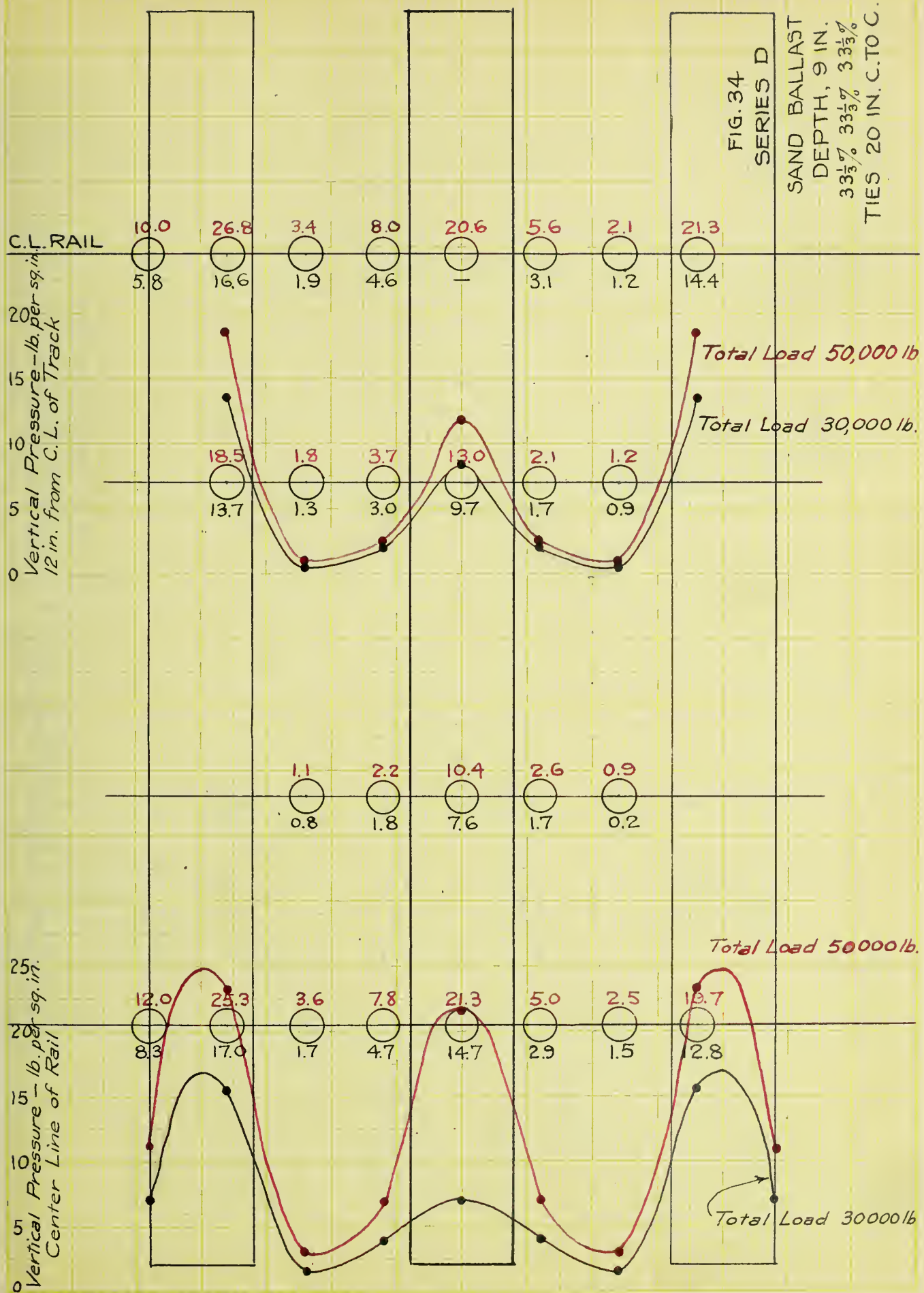
Vertical Pressure - lb. per sq. in.
Center Line of Rail.

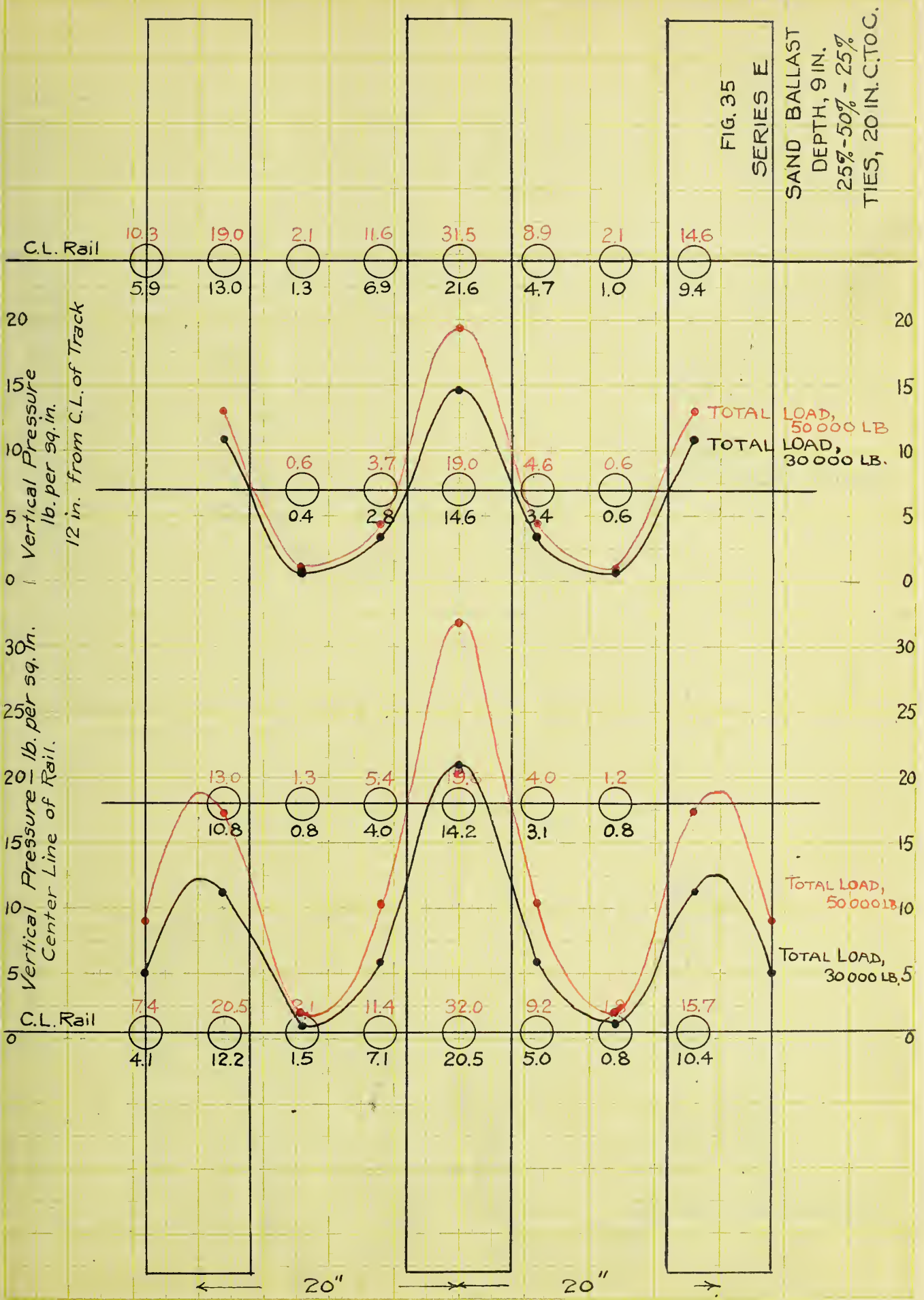


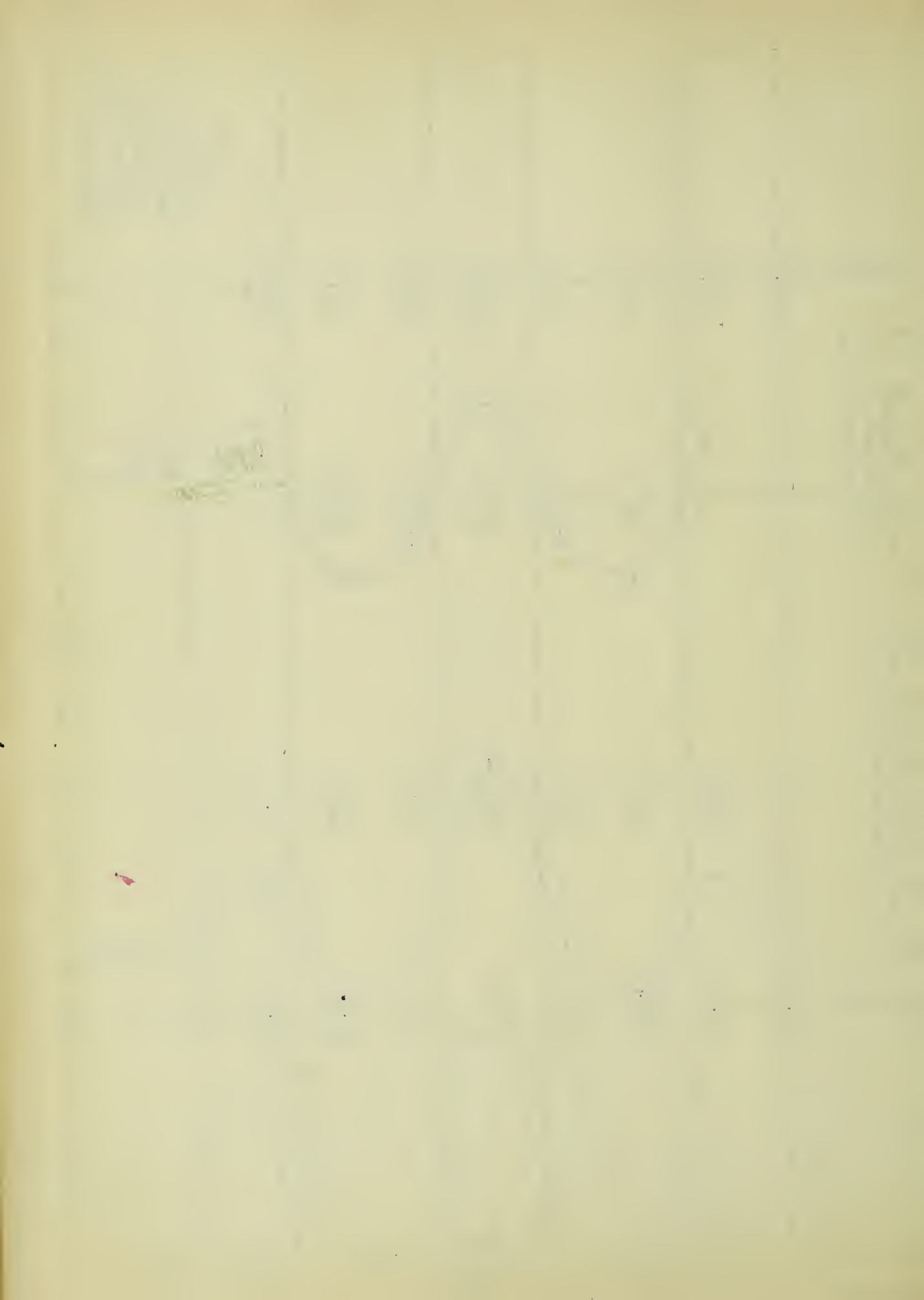
SERIES C
SAND BALLAST
DEPTH, 9 IN.
SINGLE TIE.

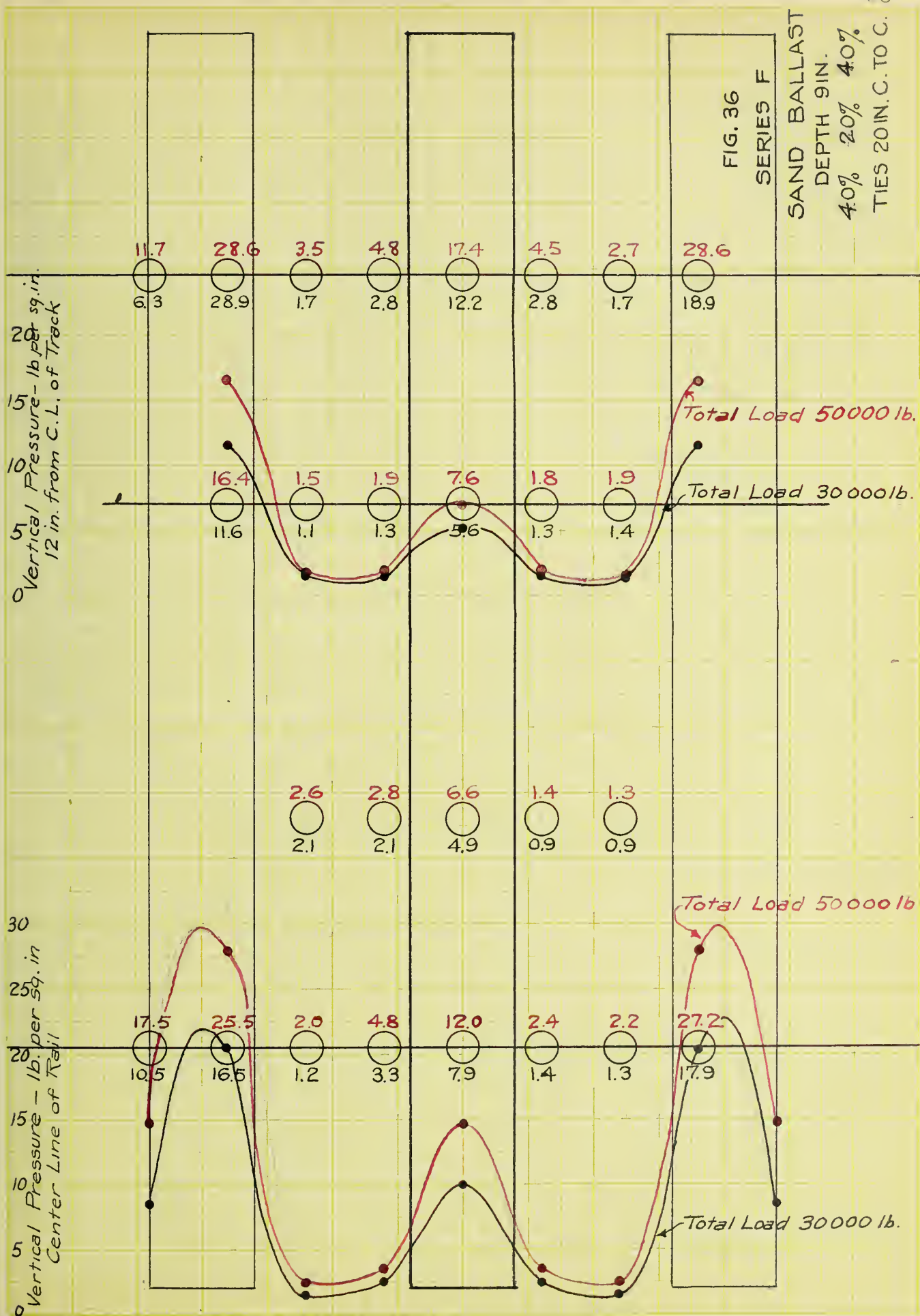
FIG. 33.

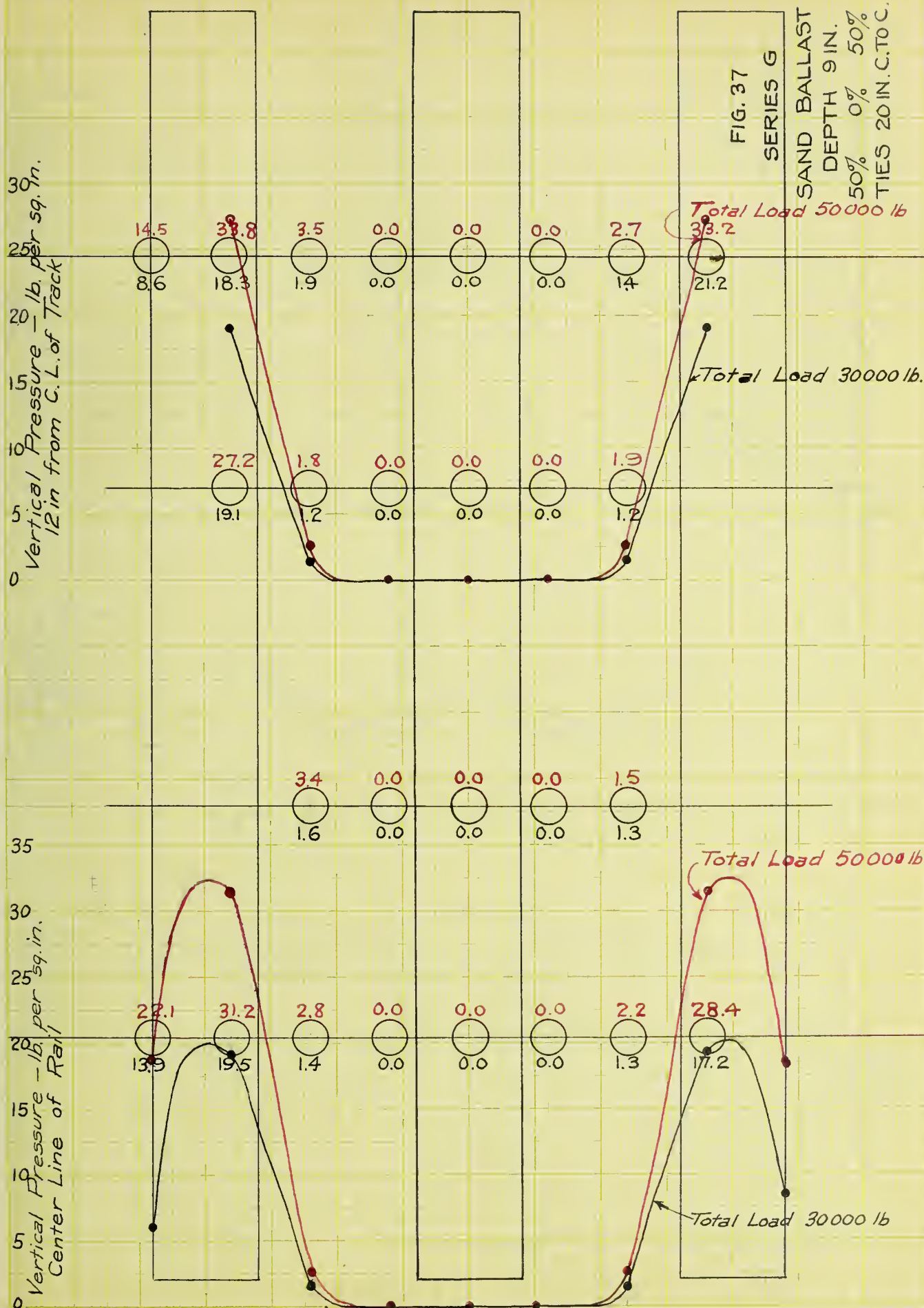


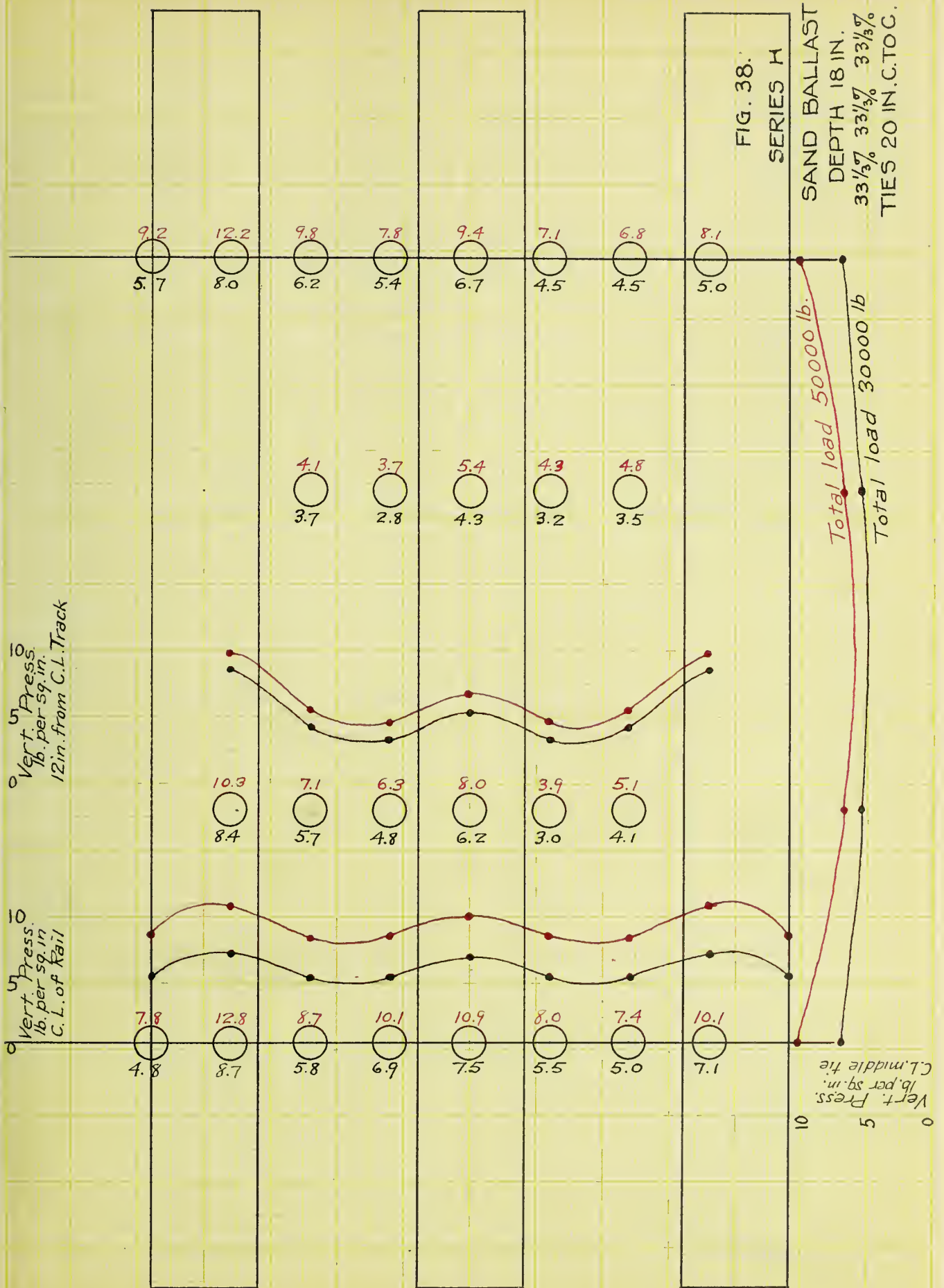


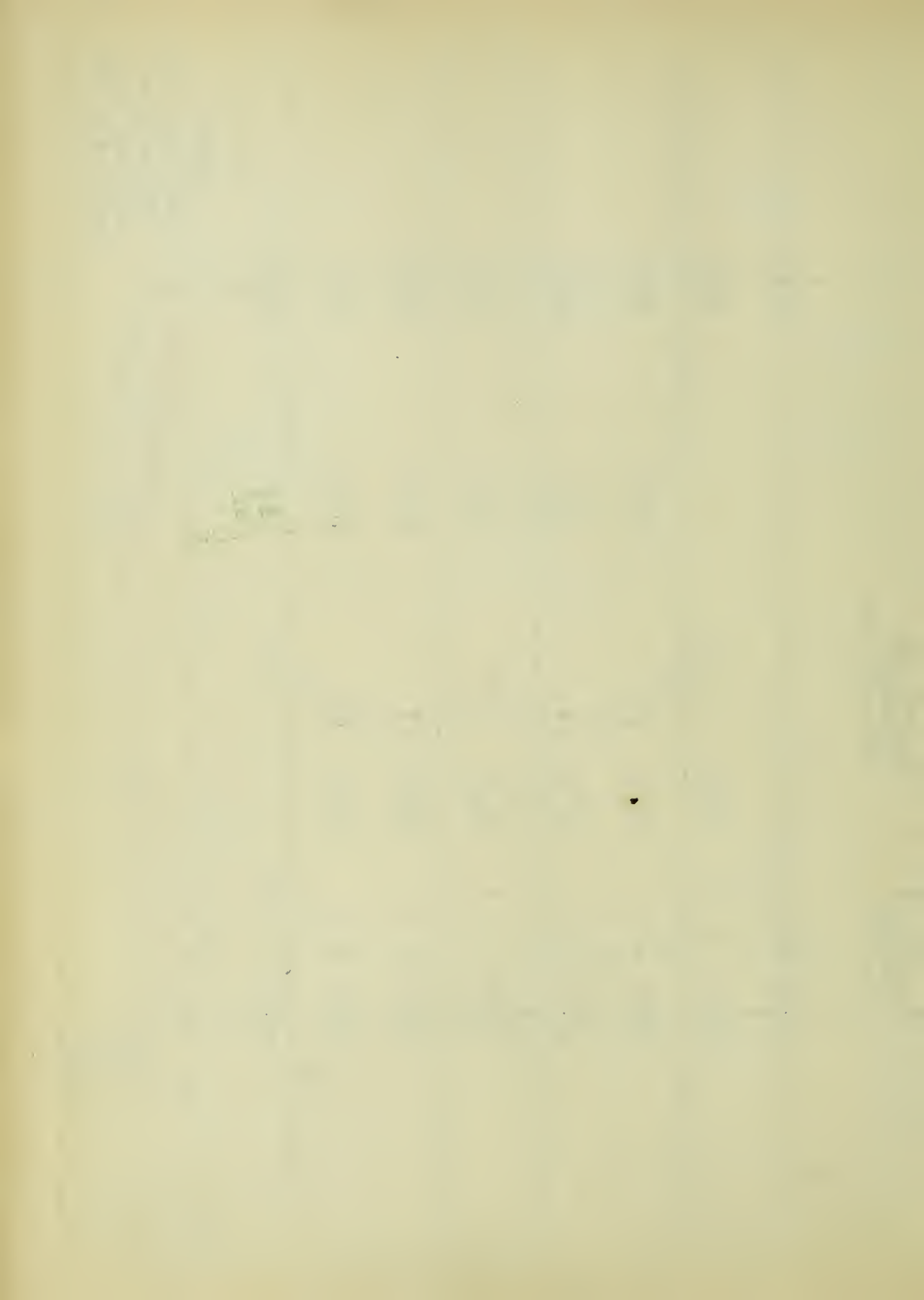












Vertical Pressure
lb. per sq. in.
C.L. of Rail

Vertical Pressure
lb. per sq. in.
12 in. from C.L. Track

7.5
5.0

11.6
7.7

8.3
5.5

12.5
8.9

15.2
10.2

11.6
7.3

6.9
4.3

8.7
6.0

8.2
6.6

6.1
4.6

8.1
6.2

11.2
8.7

6.6
4.5

4.4
3.5

3.3
2.6

4.3
3.2

8.0
5.9

6.6
4.8

4.4
3.0

8.3
5.5

10.6
7.2

9.1
5.8

10.4
7.1

13.5
9.4

10.0
6.8

6.6
3.9

6.6
1.4

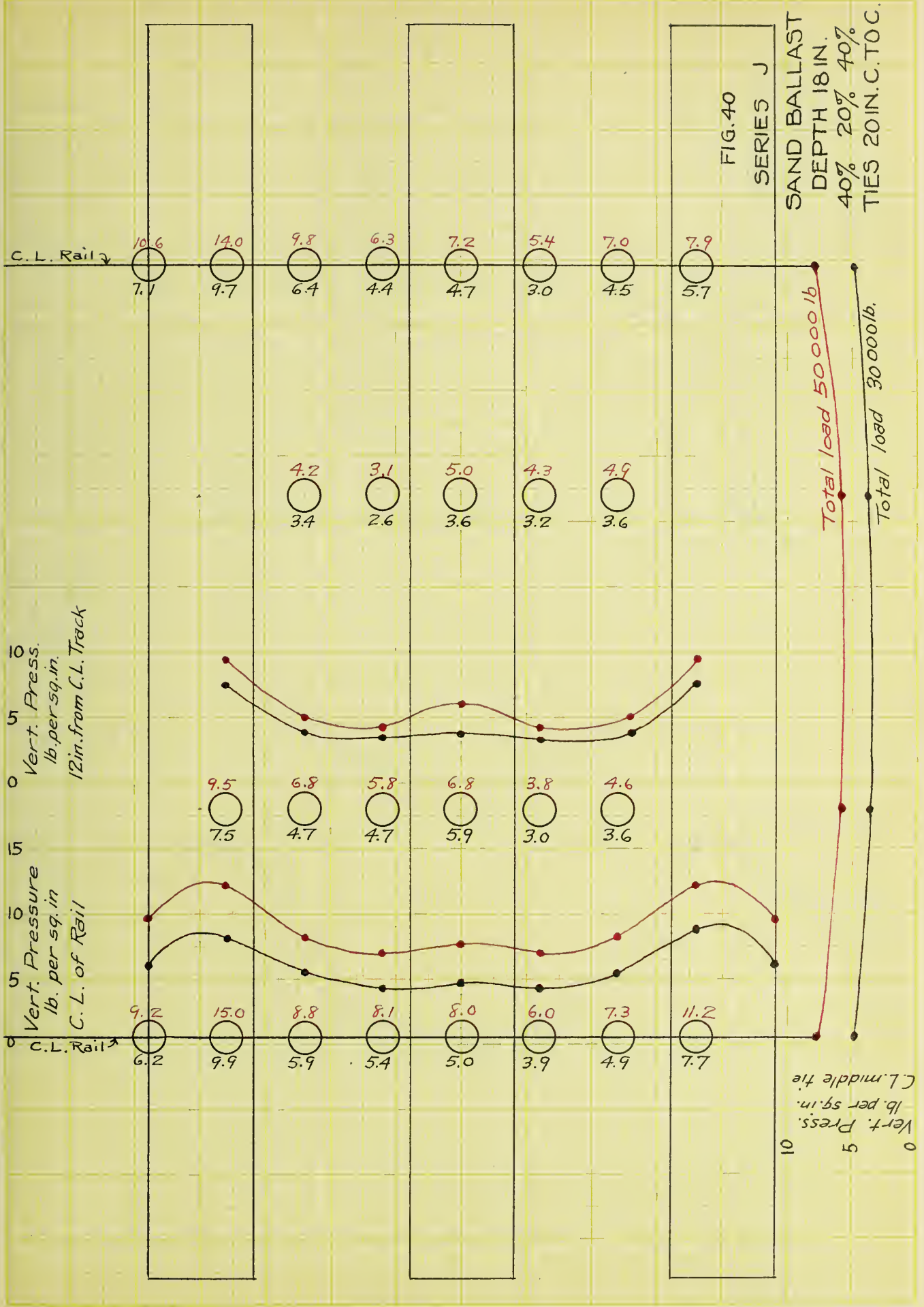
Vertical Pressure
lb. per sq. in.
C.L. of middle tie

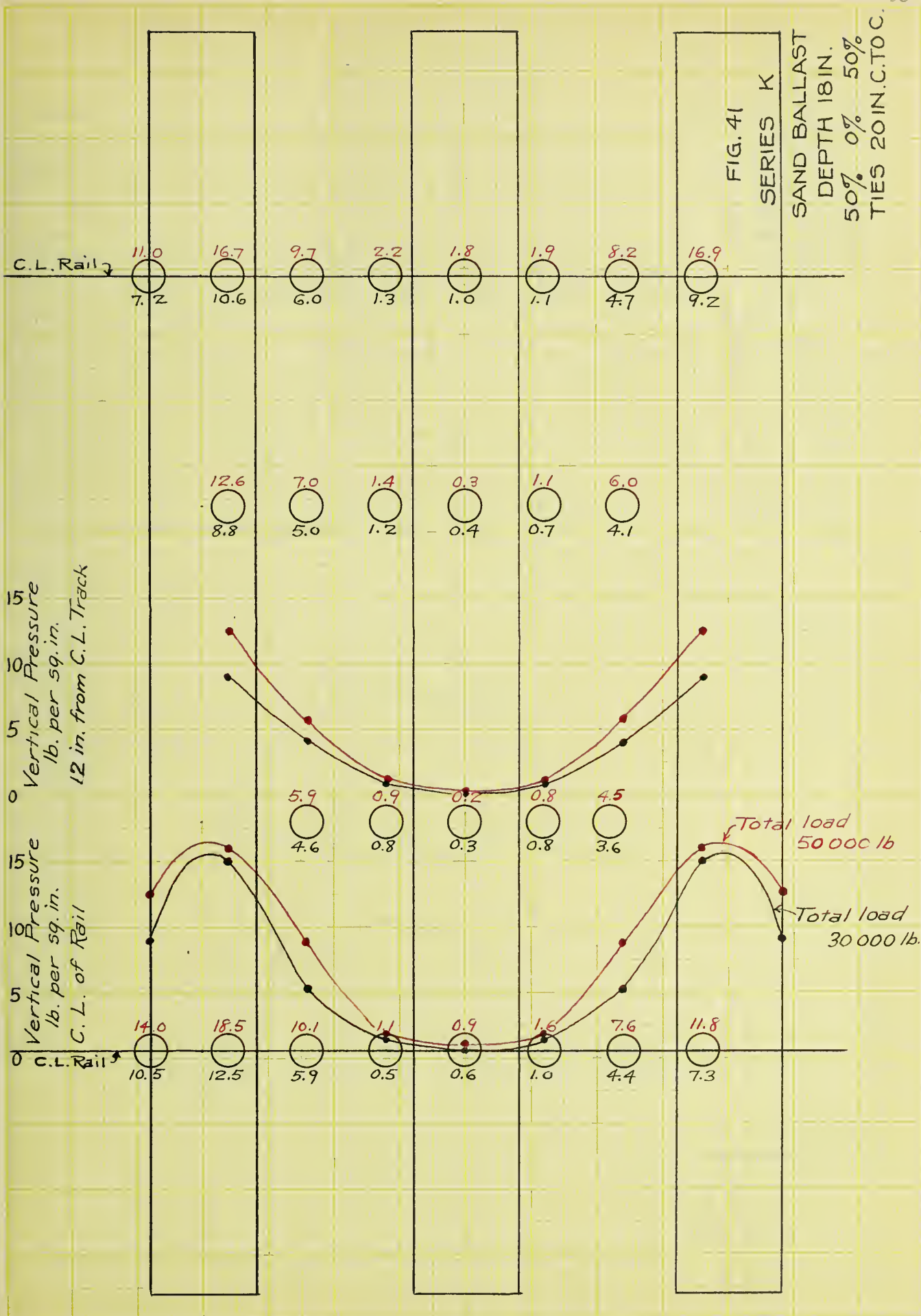
FIG. 39
SERIES I

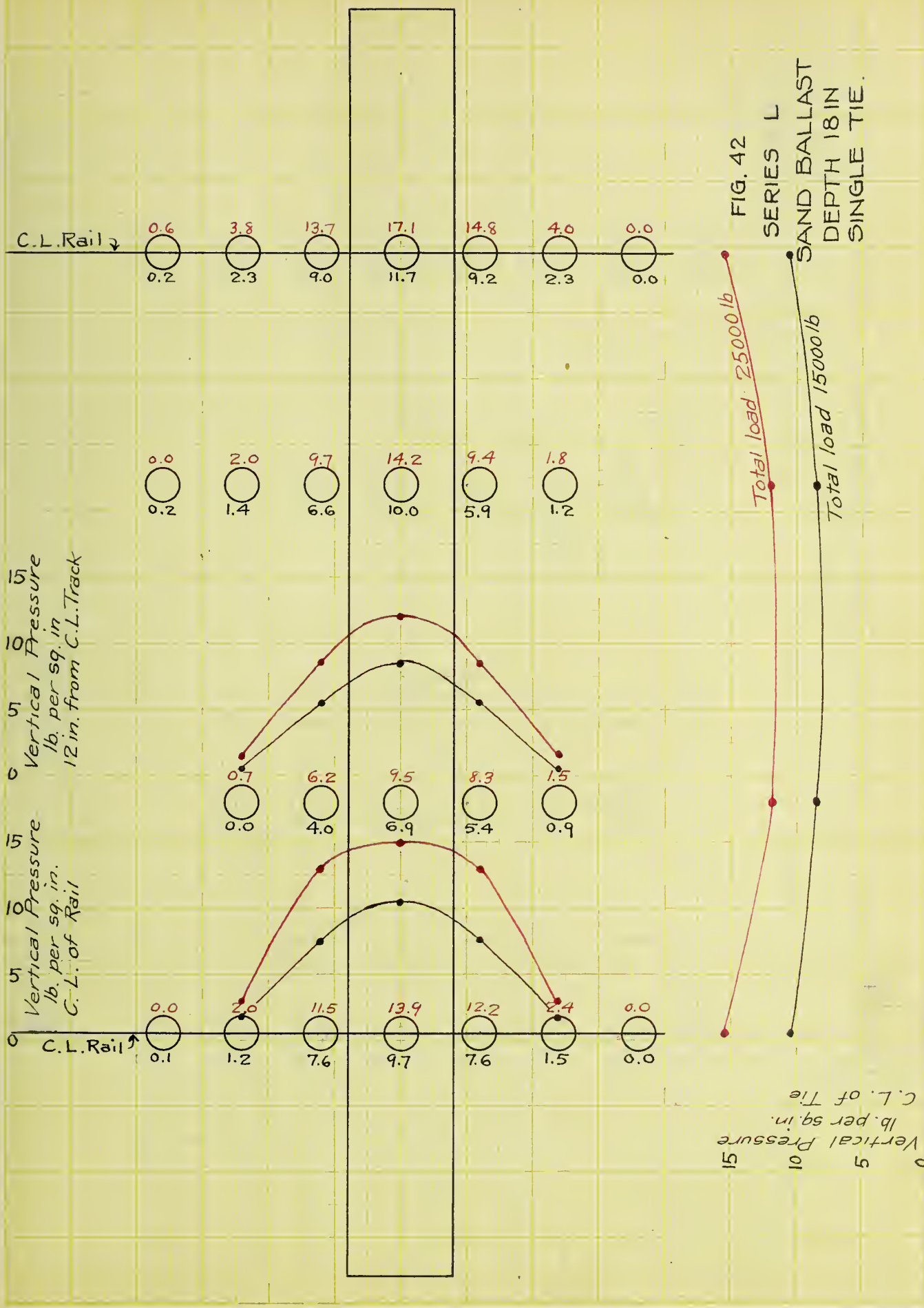
SAND BALLAST
DEPTH 18 IN.
25% 50% 25%
TIES 20 IN. C.T.O.C.

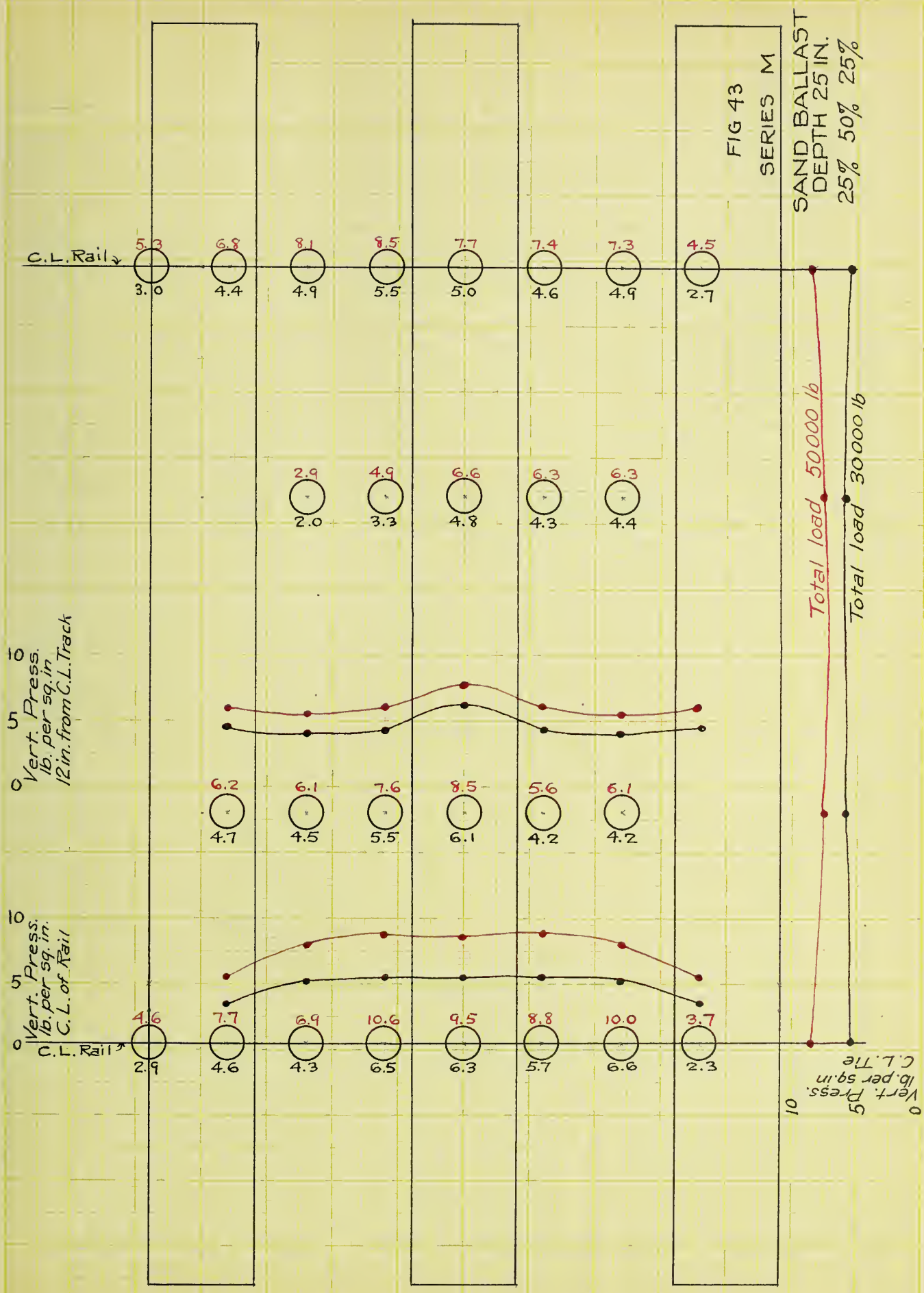
Total load 50000 lb

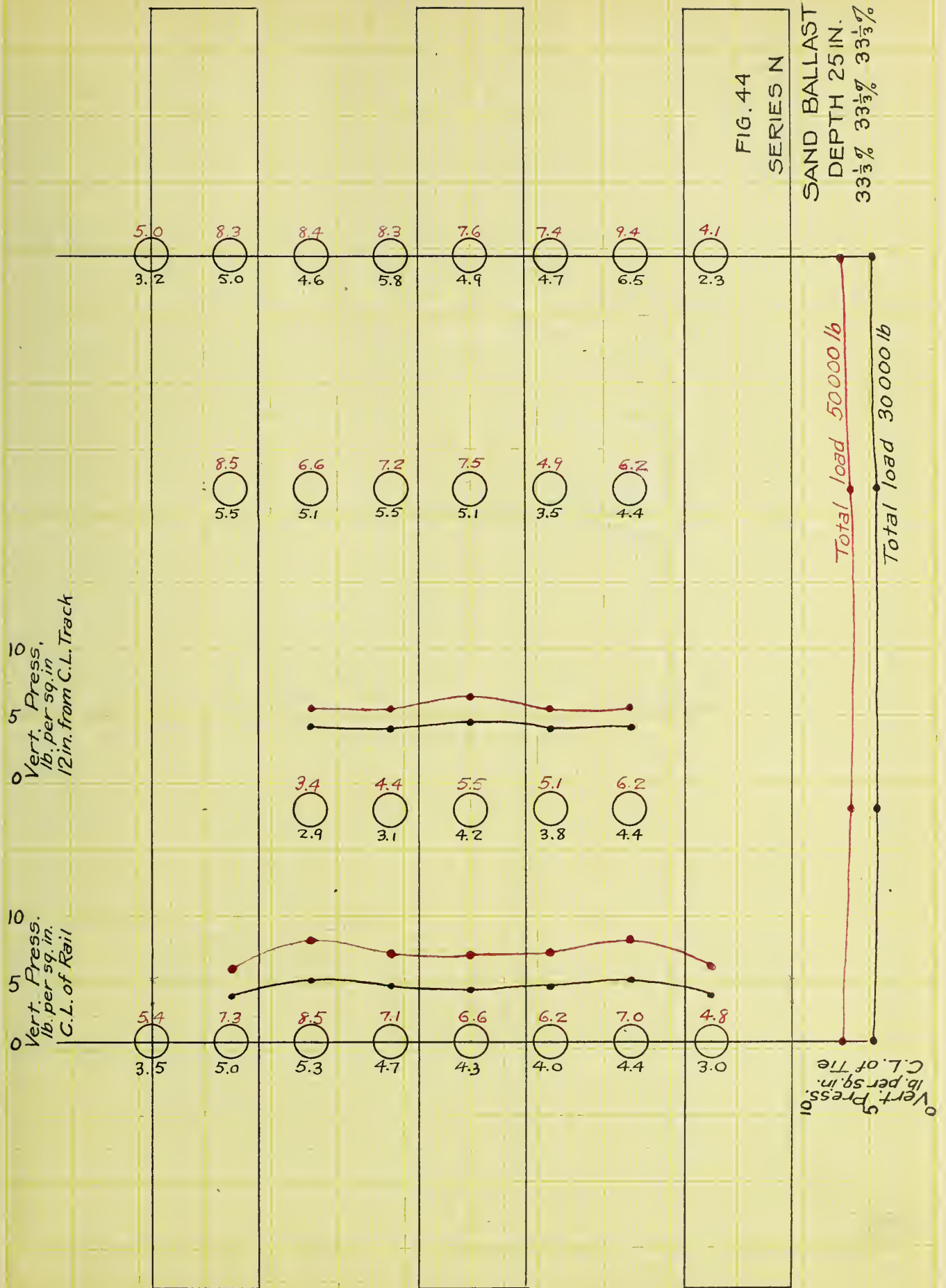
Total load 30000 lb

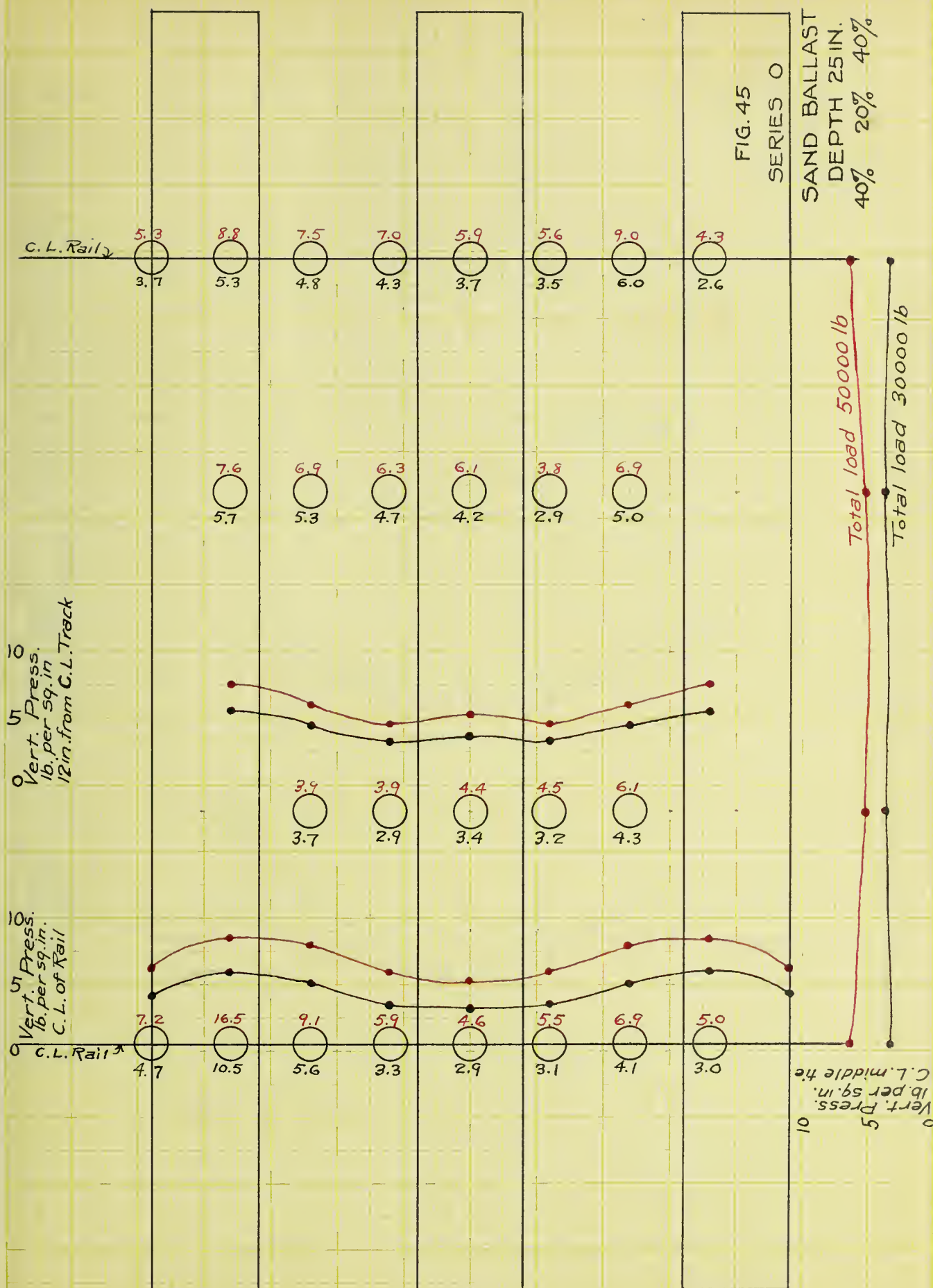


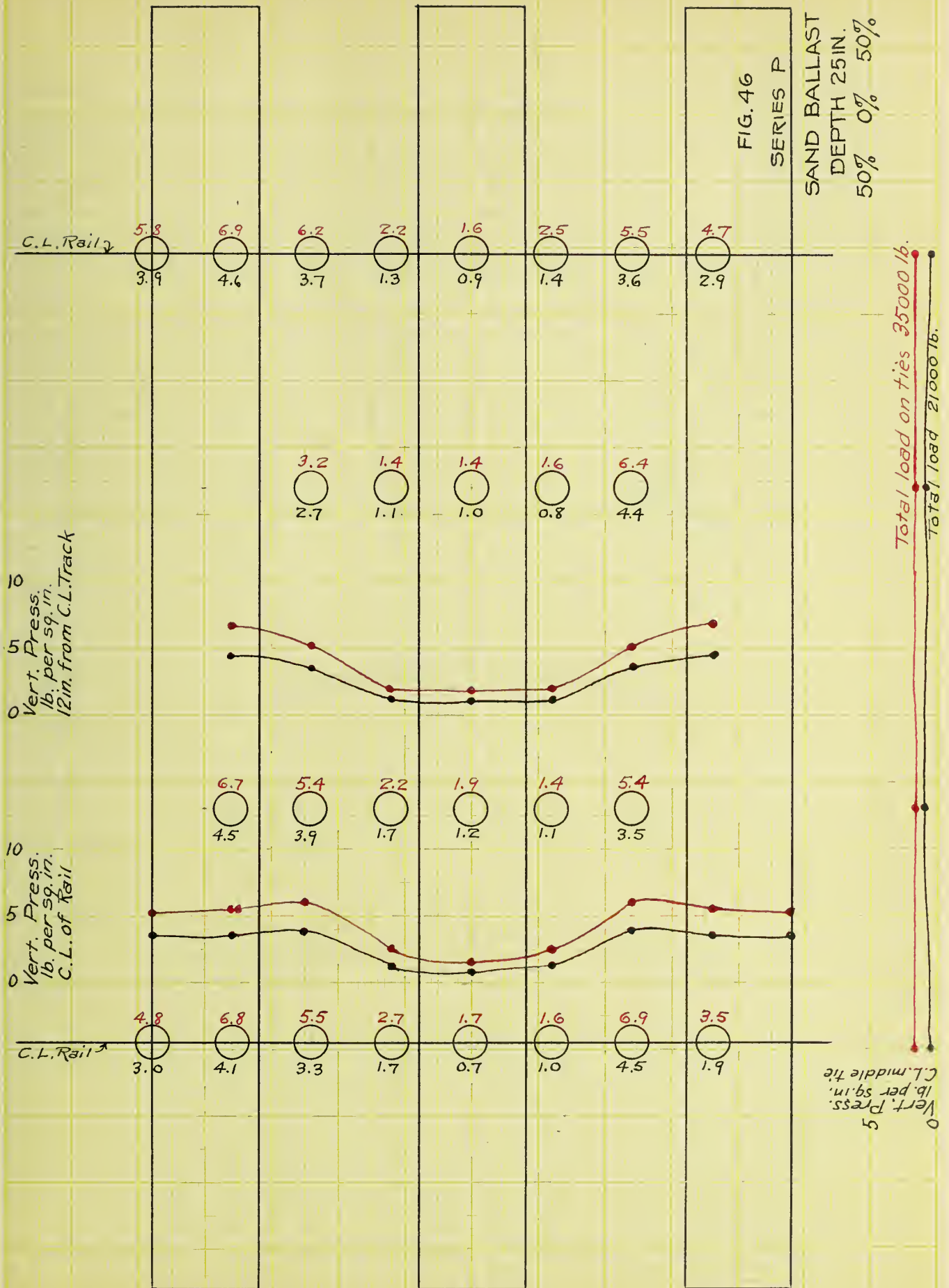


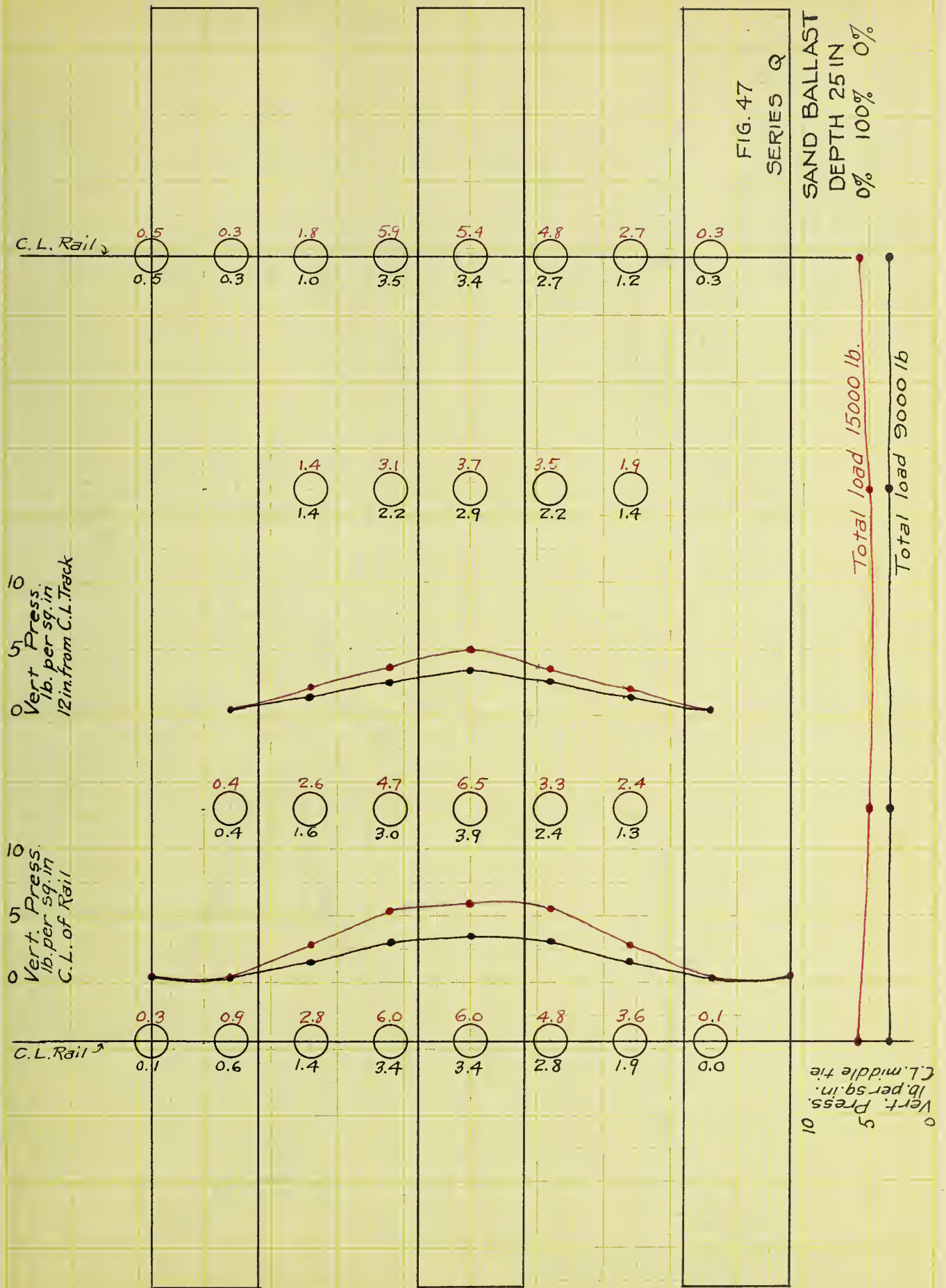


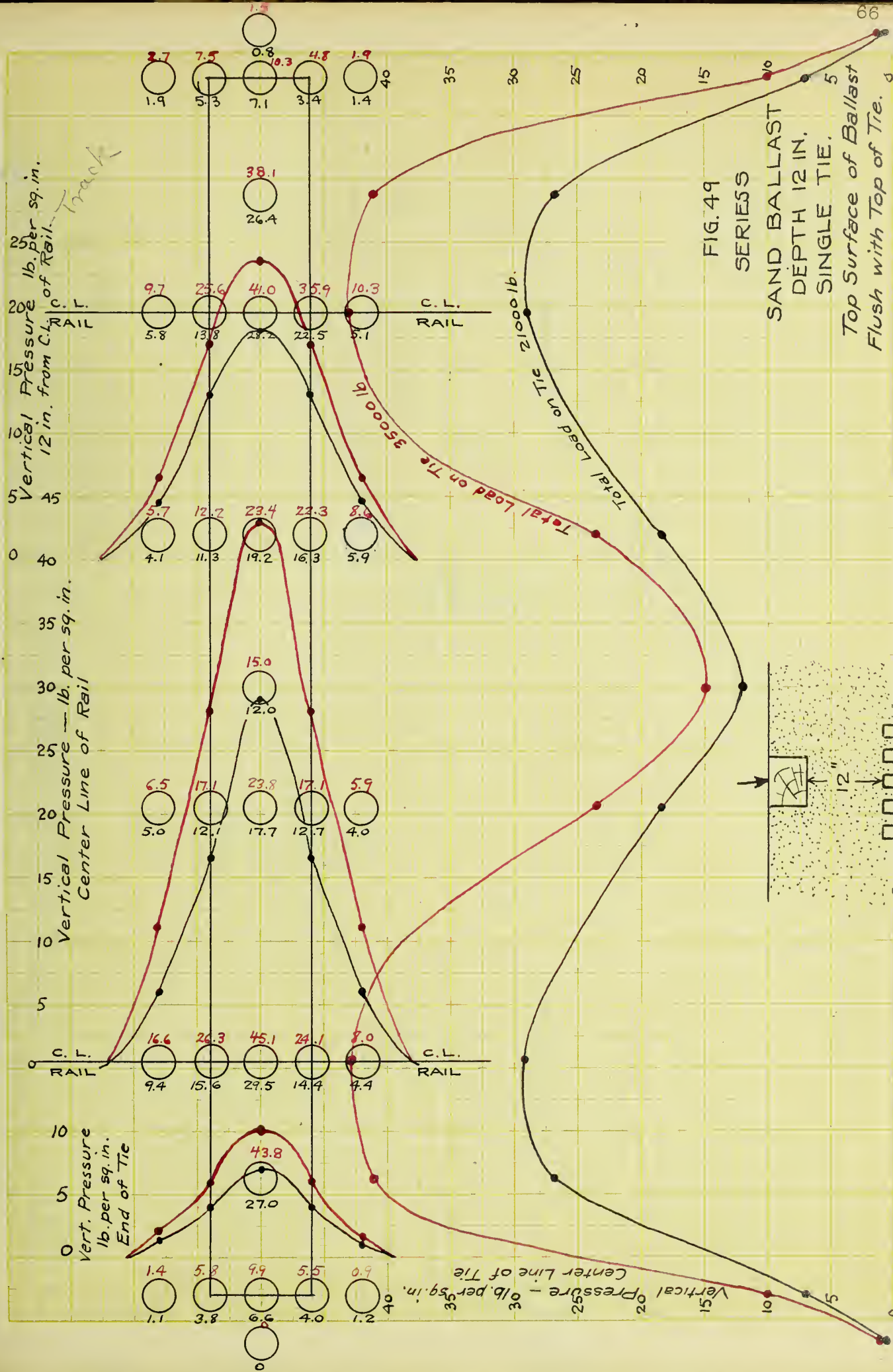


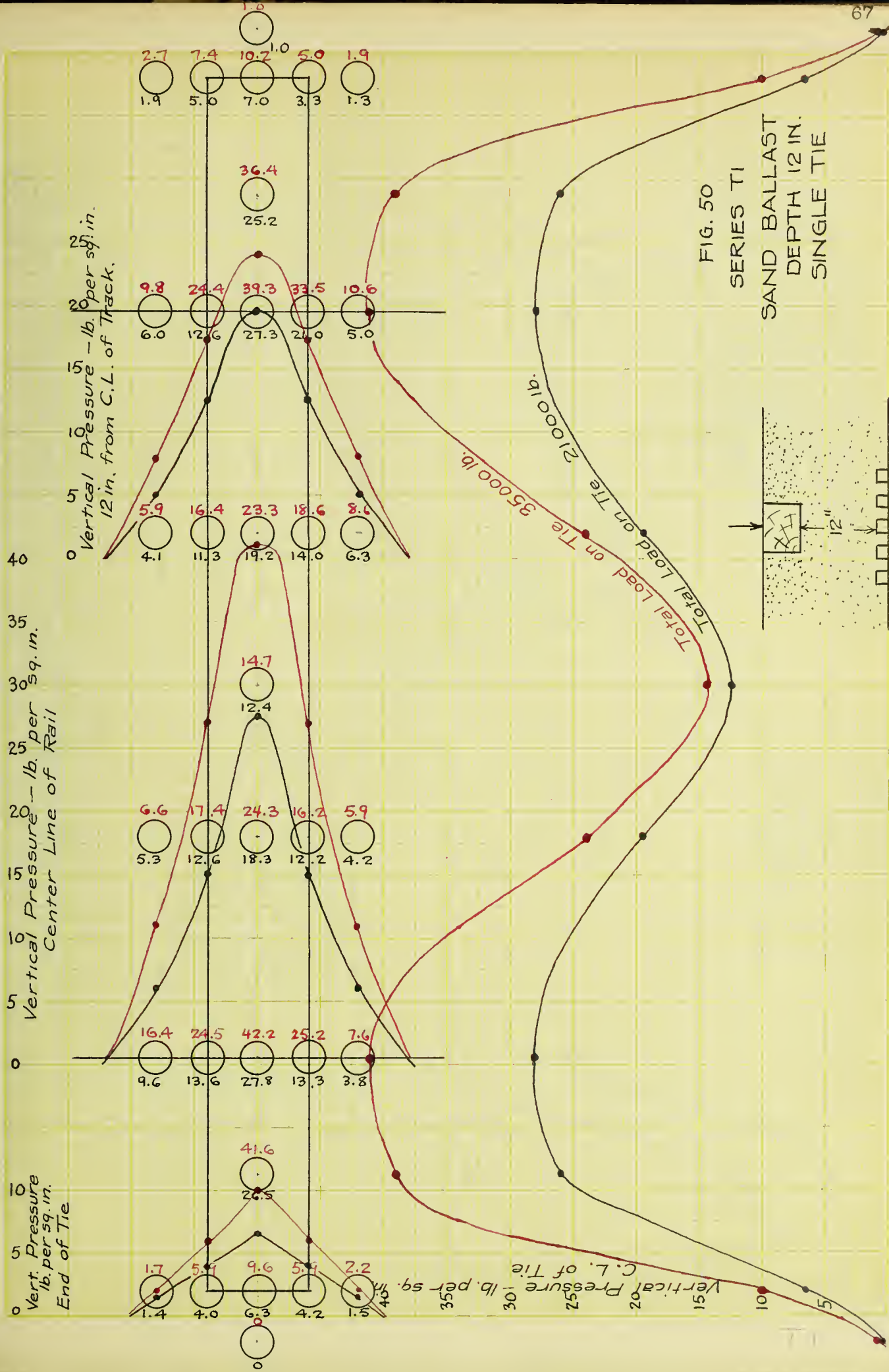


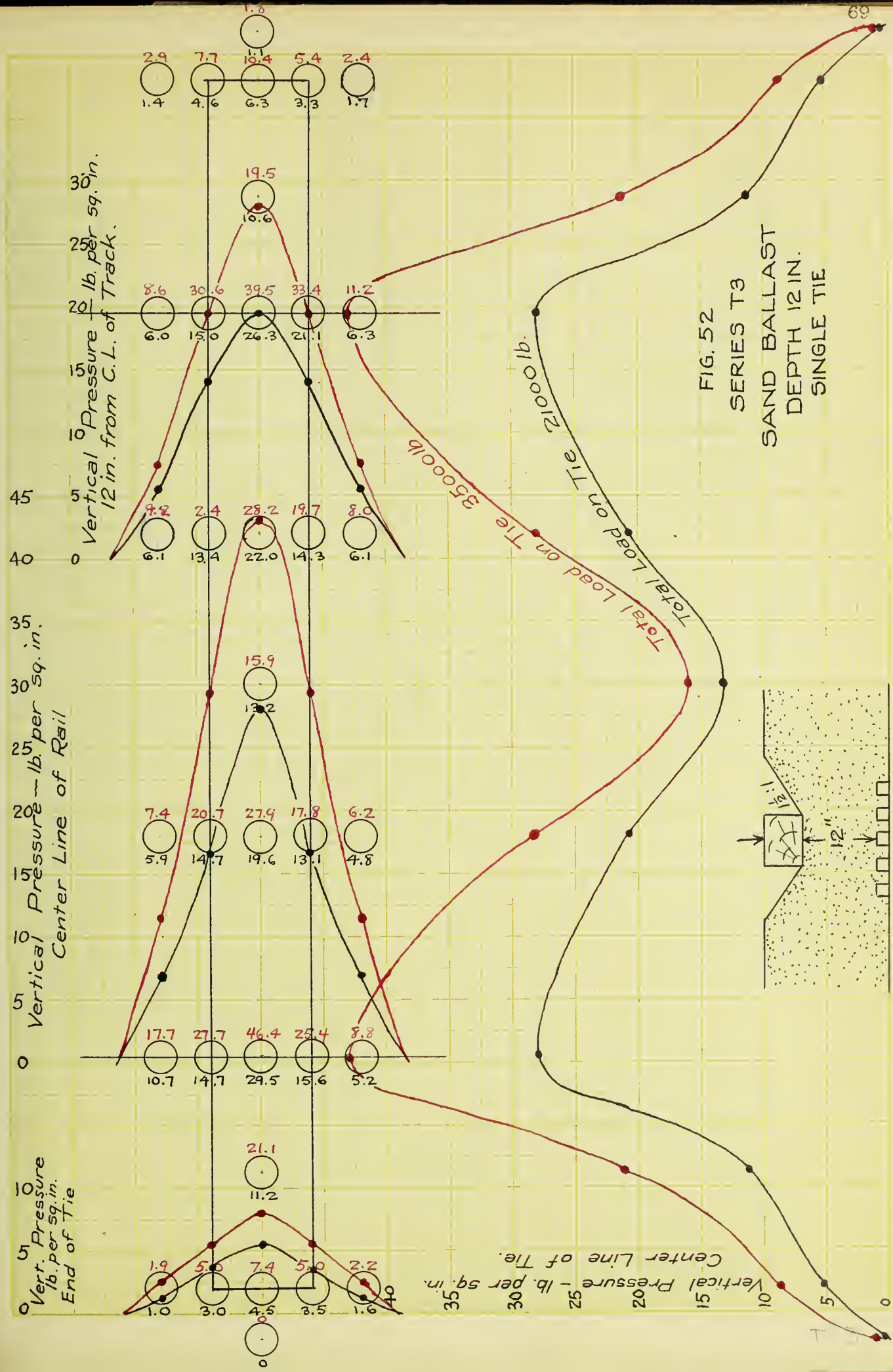


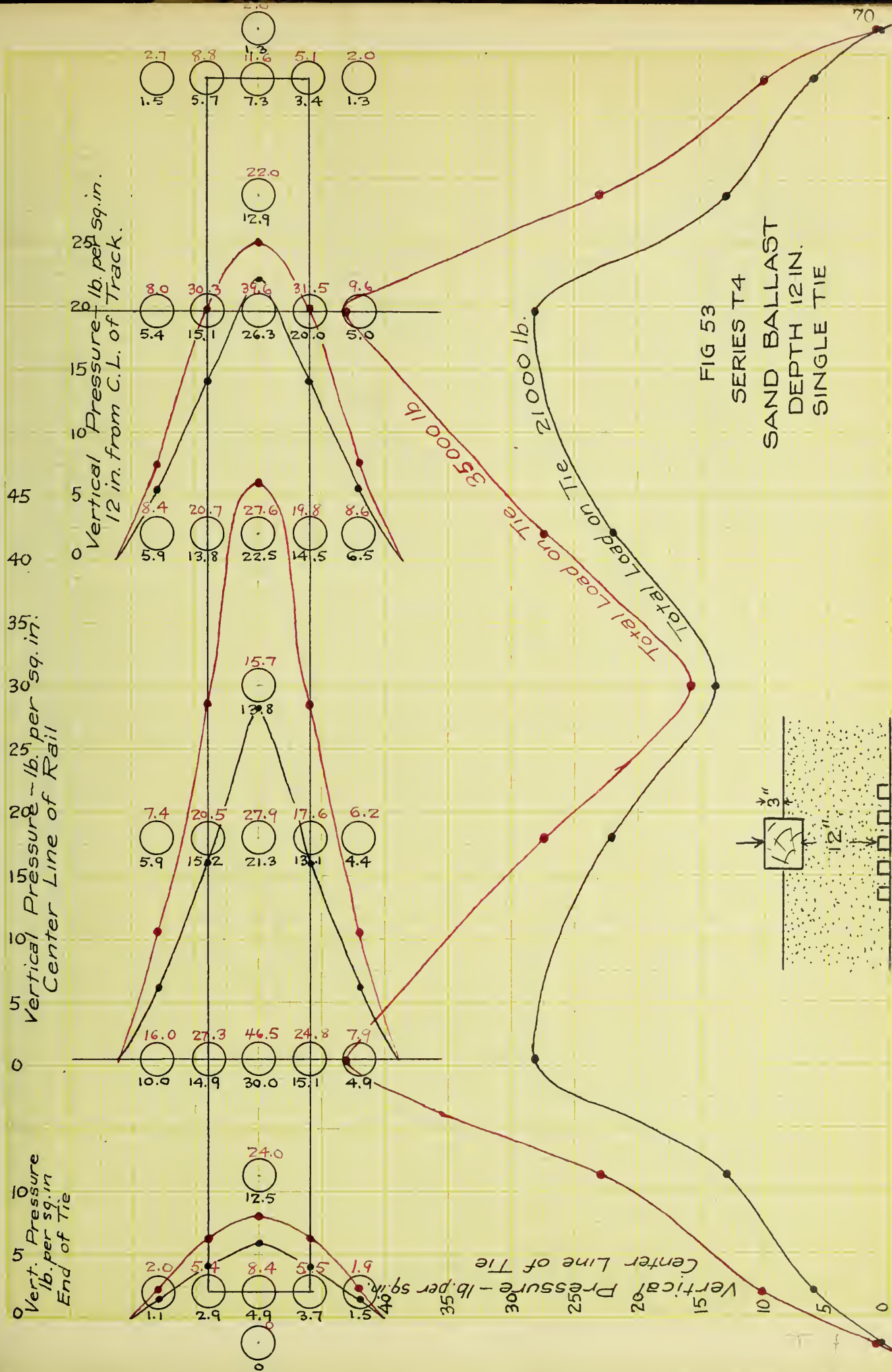


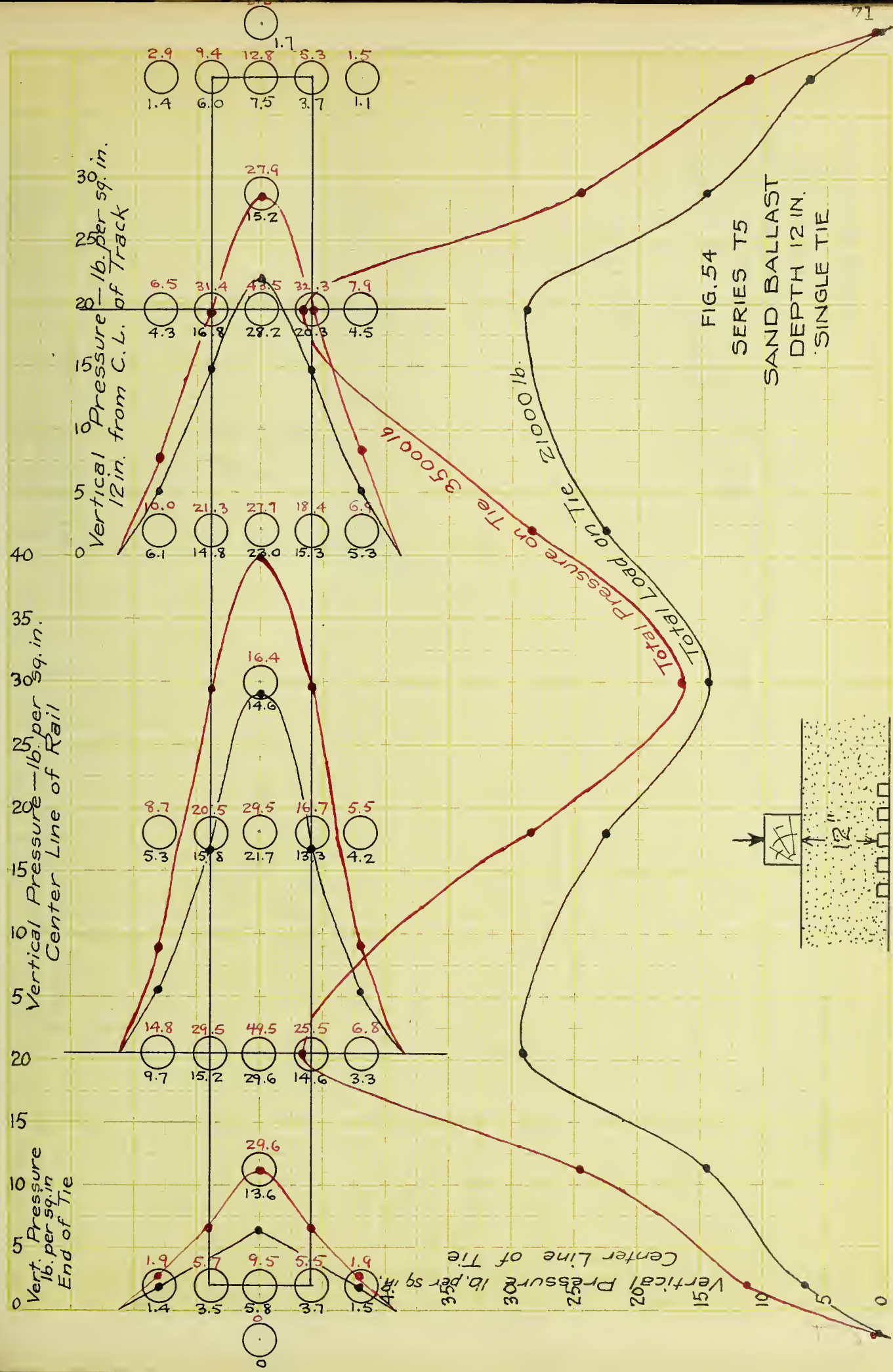








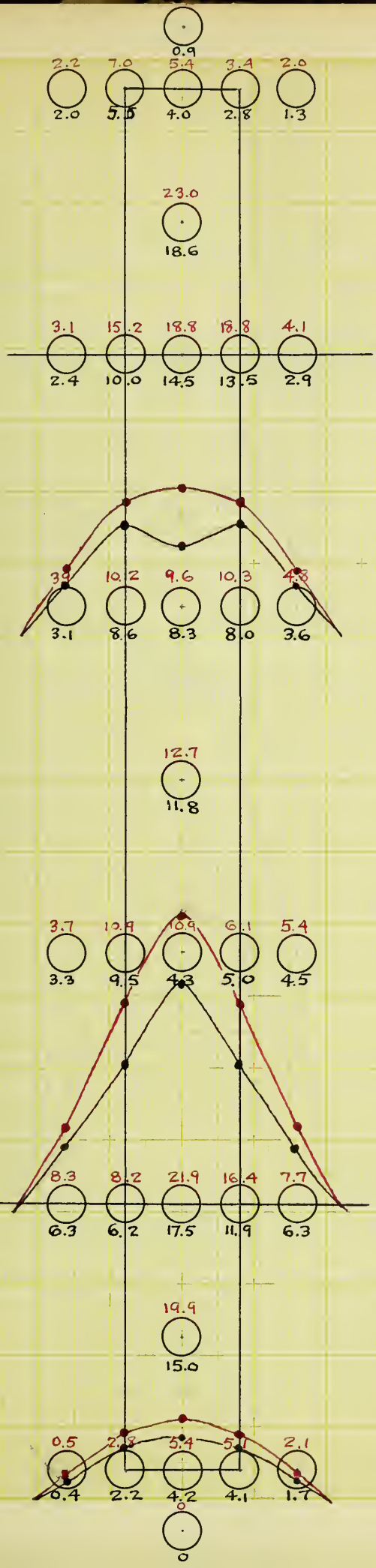




Vert. Pressure
lb. per sq. in.
12 in. from C.L. of Track

Vertical Pressure - lb. per sq. in.
Center Line of Rail

Vert. Pressure
lb. per sq. in.
End of Tie

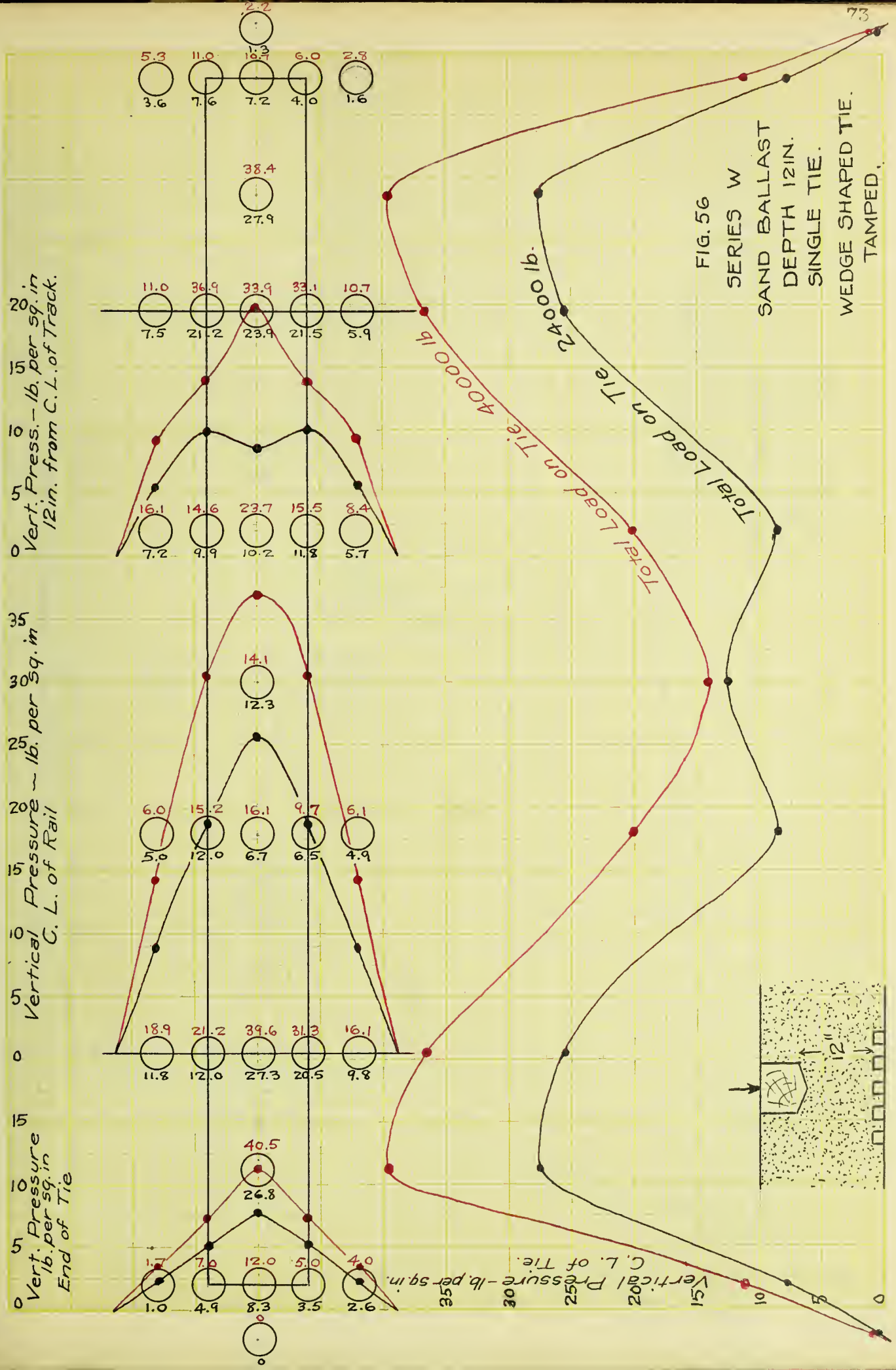


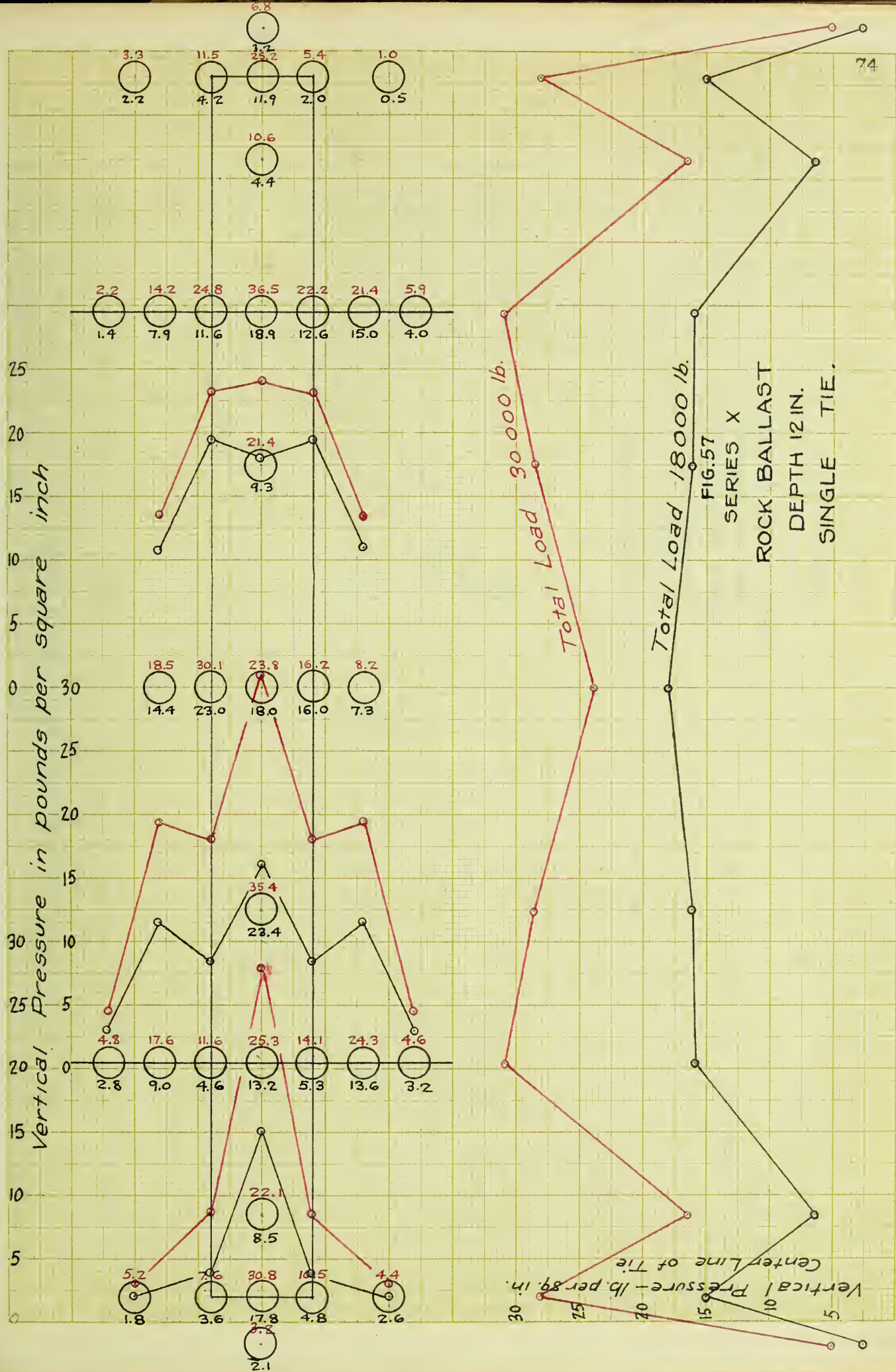
Vert. Press. - lb. per sq. in.
C.L. of Tie

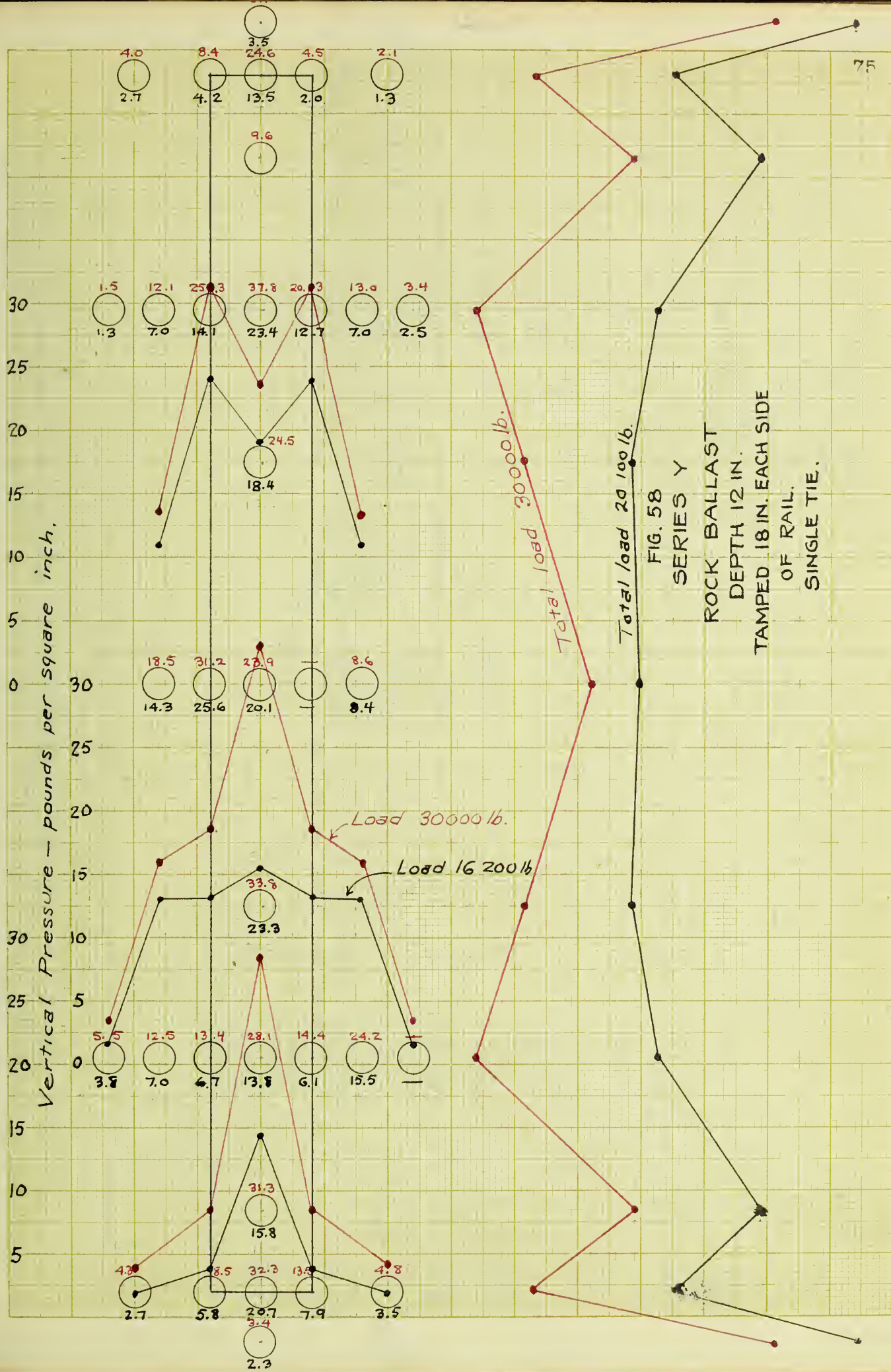


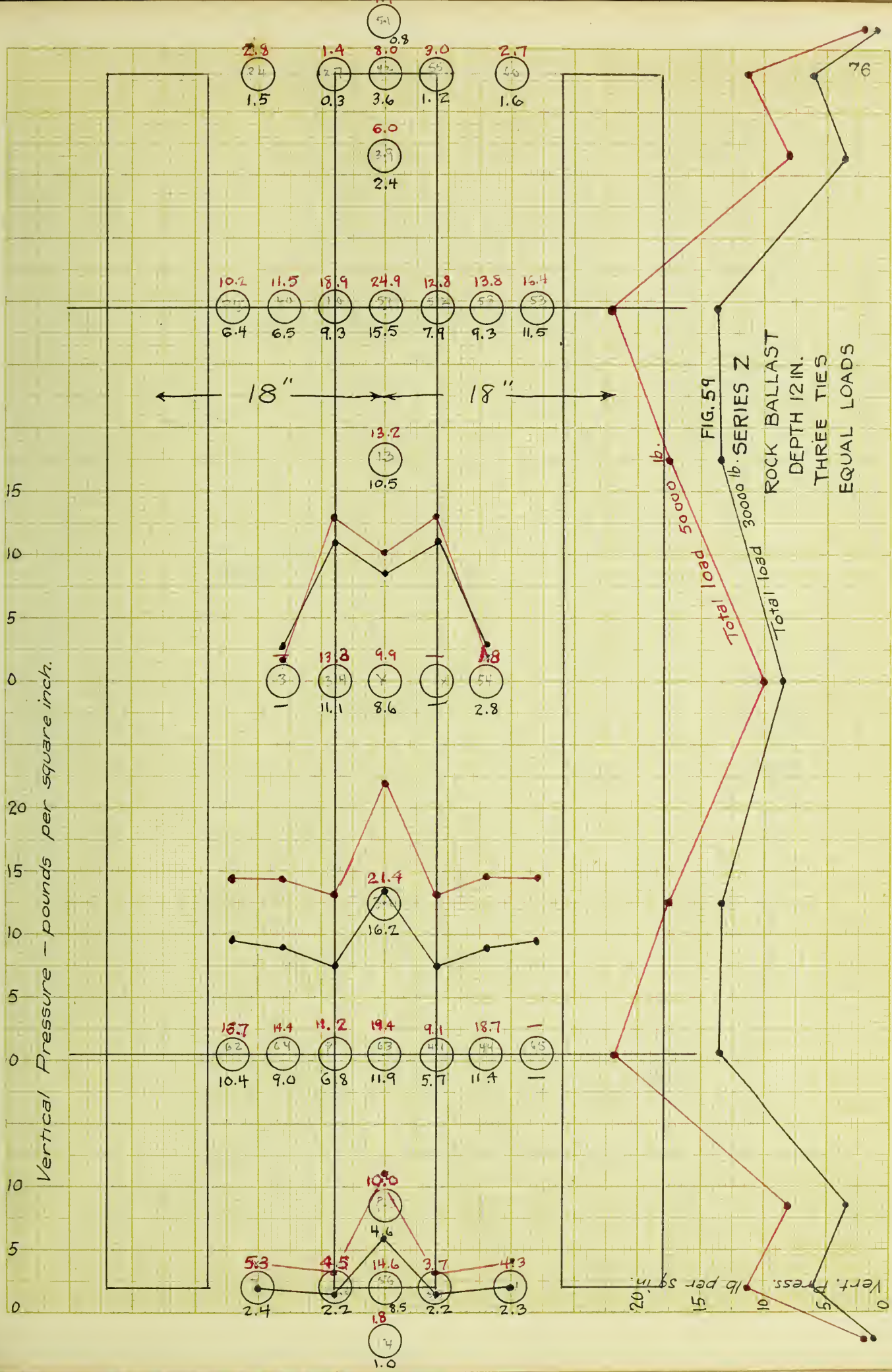
FIG. 55

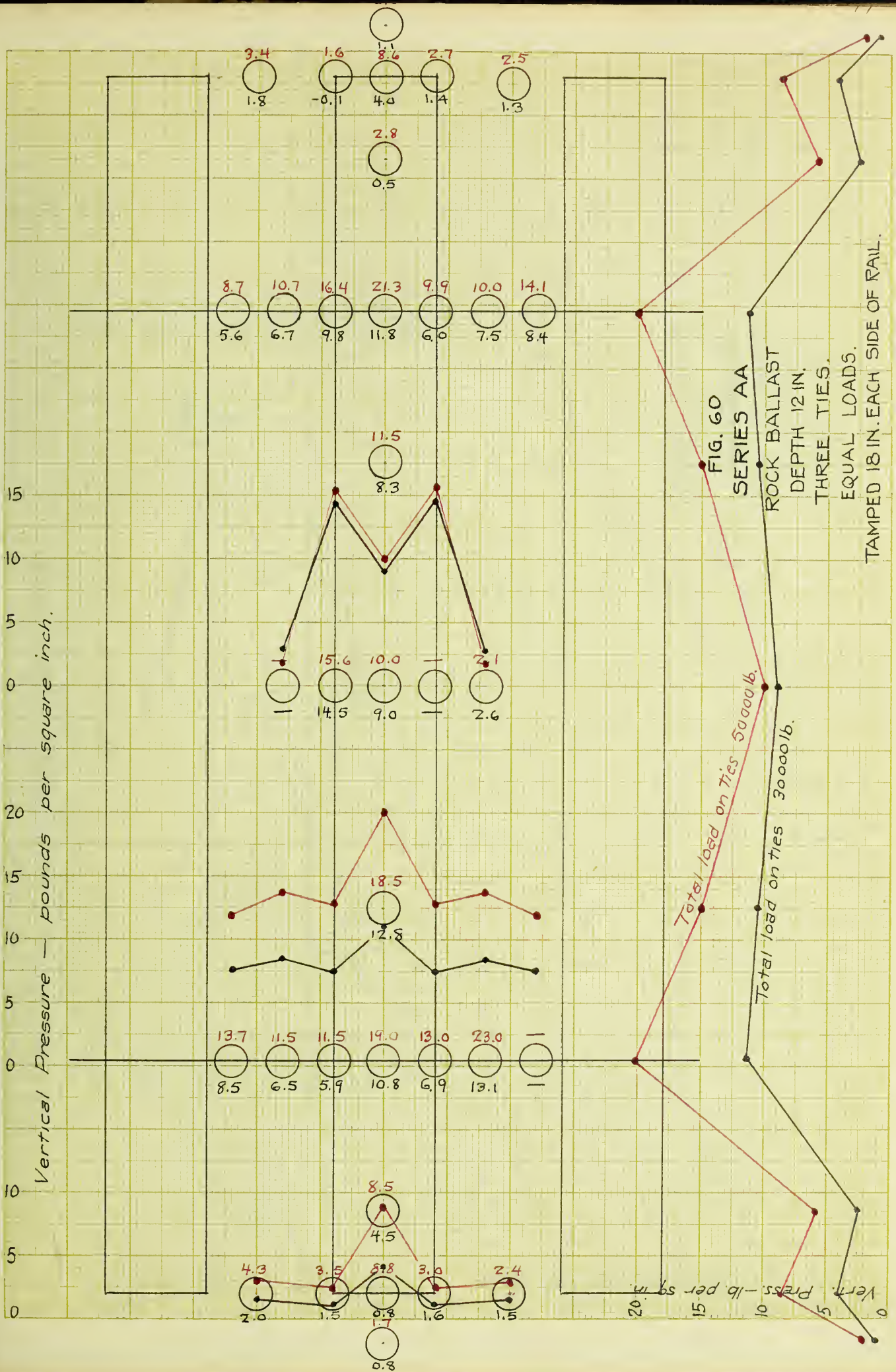
SERIES V
SAND BALLAST
DEPTH 12 IN
SINGLE TIE
WEDGE SHAPED TIE

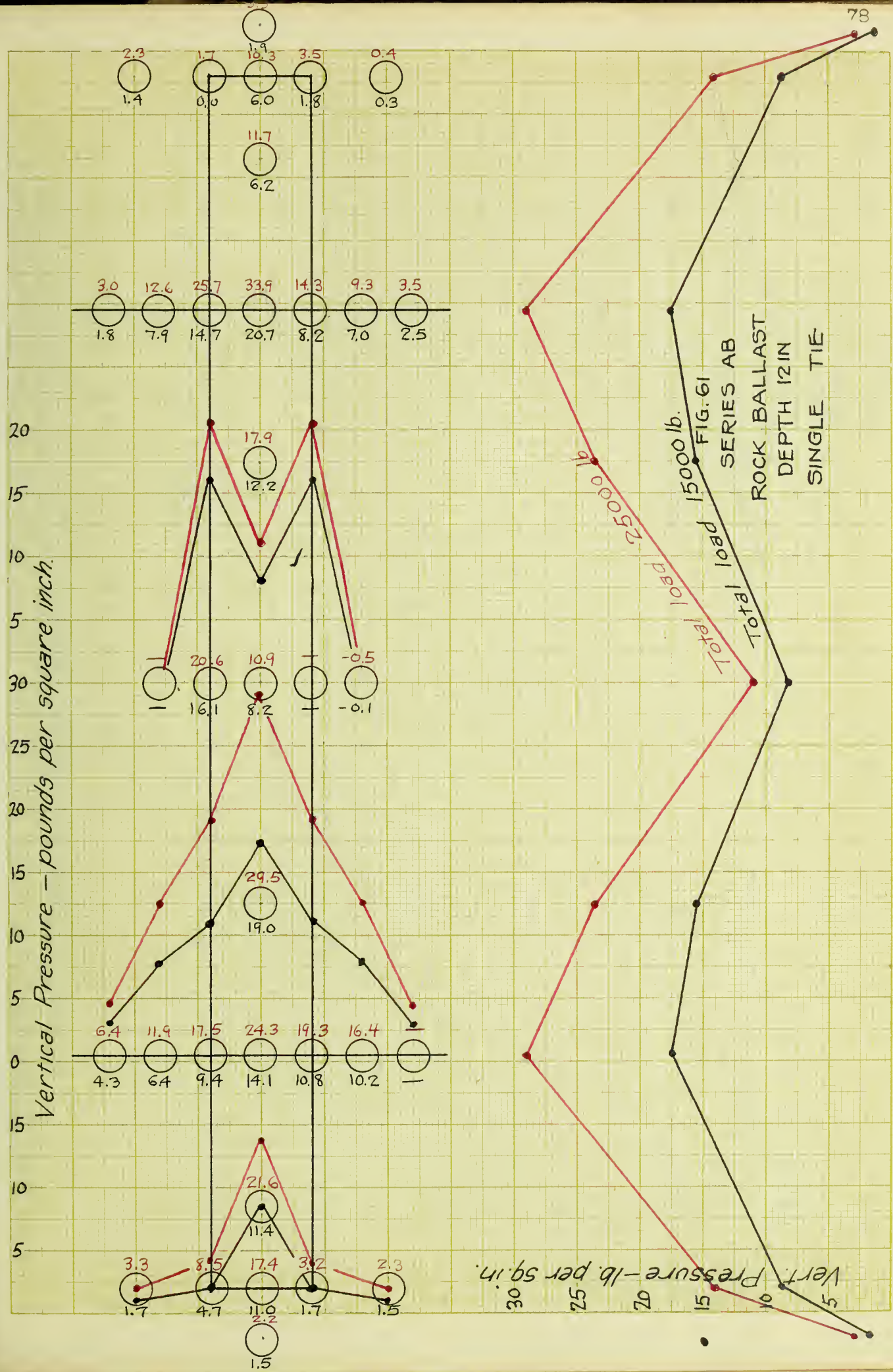


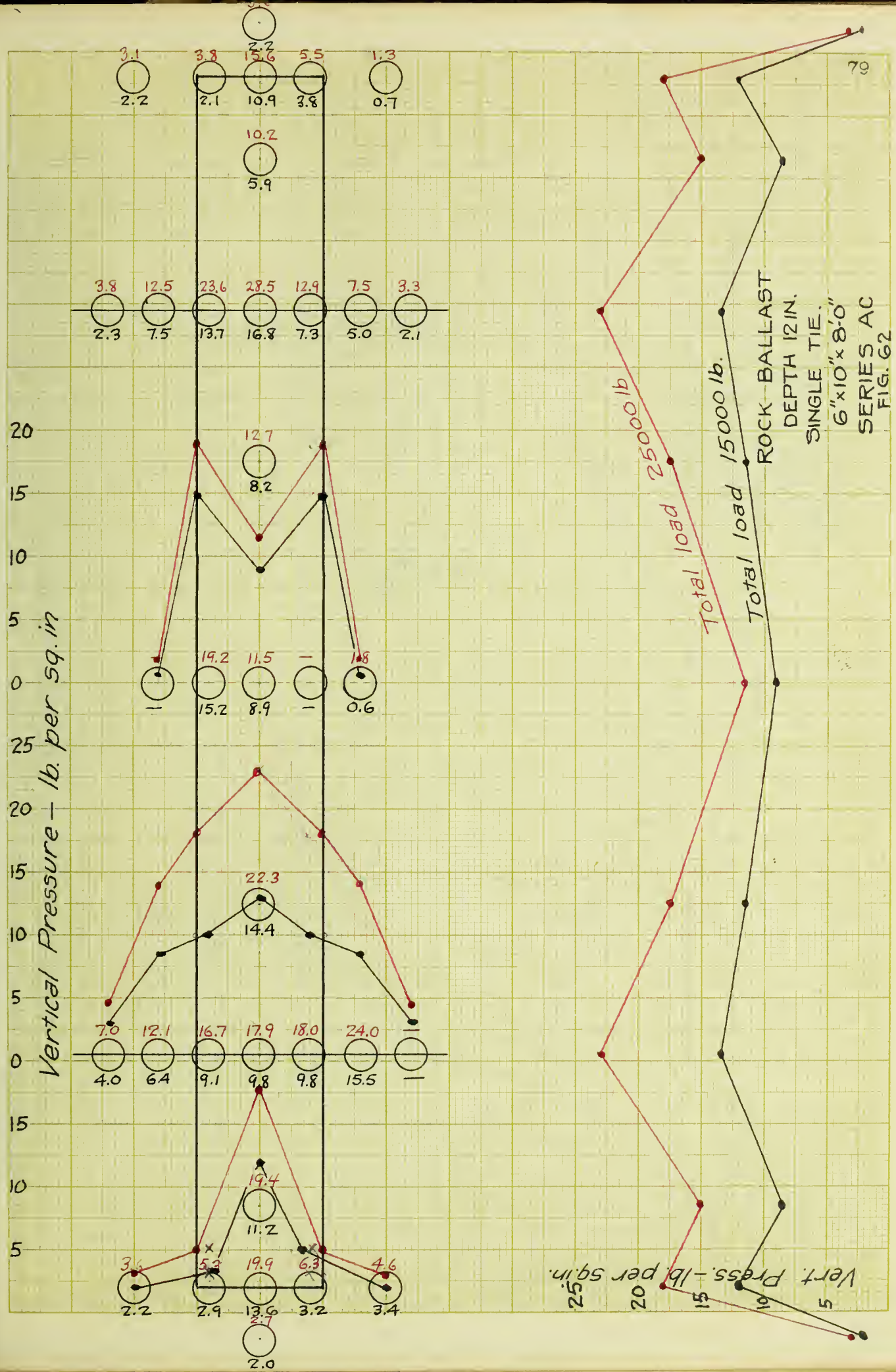


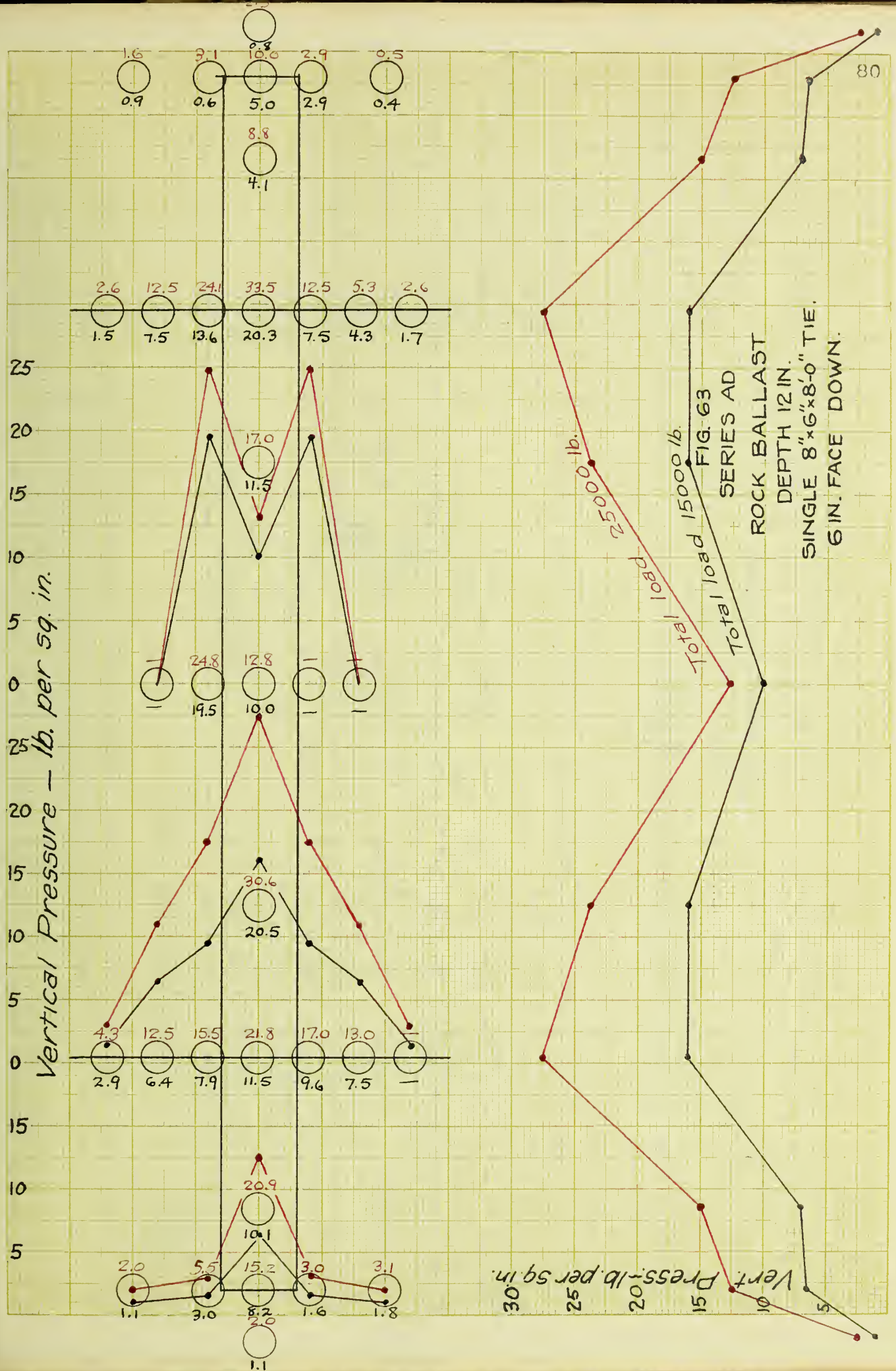


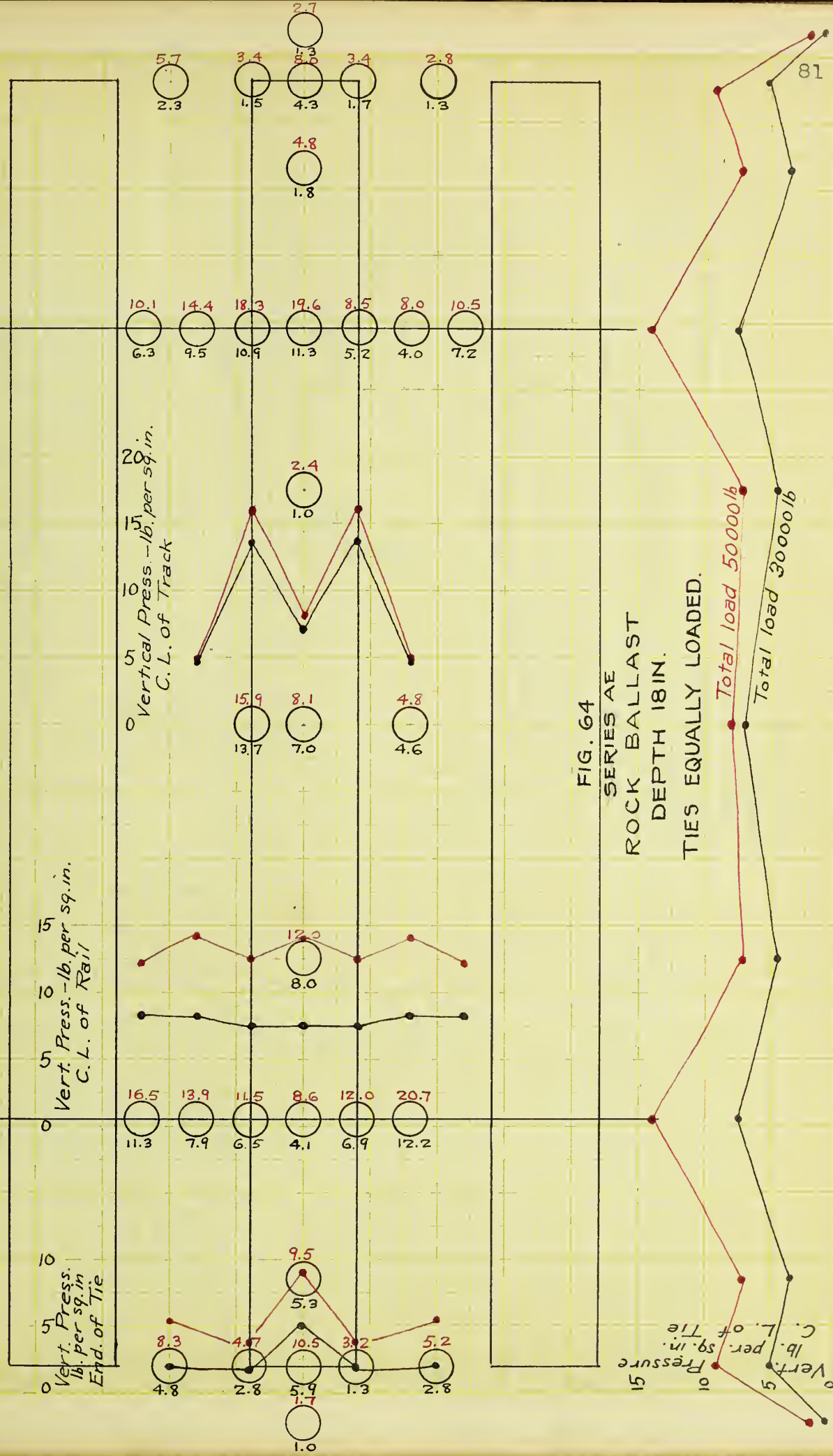












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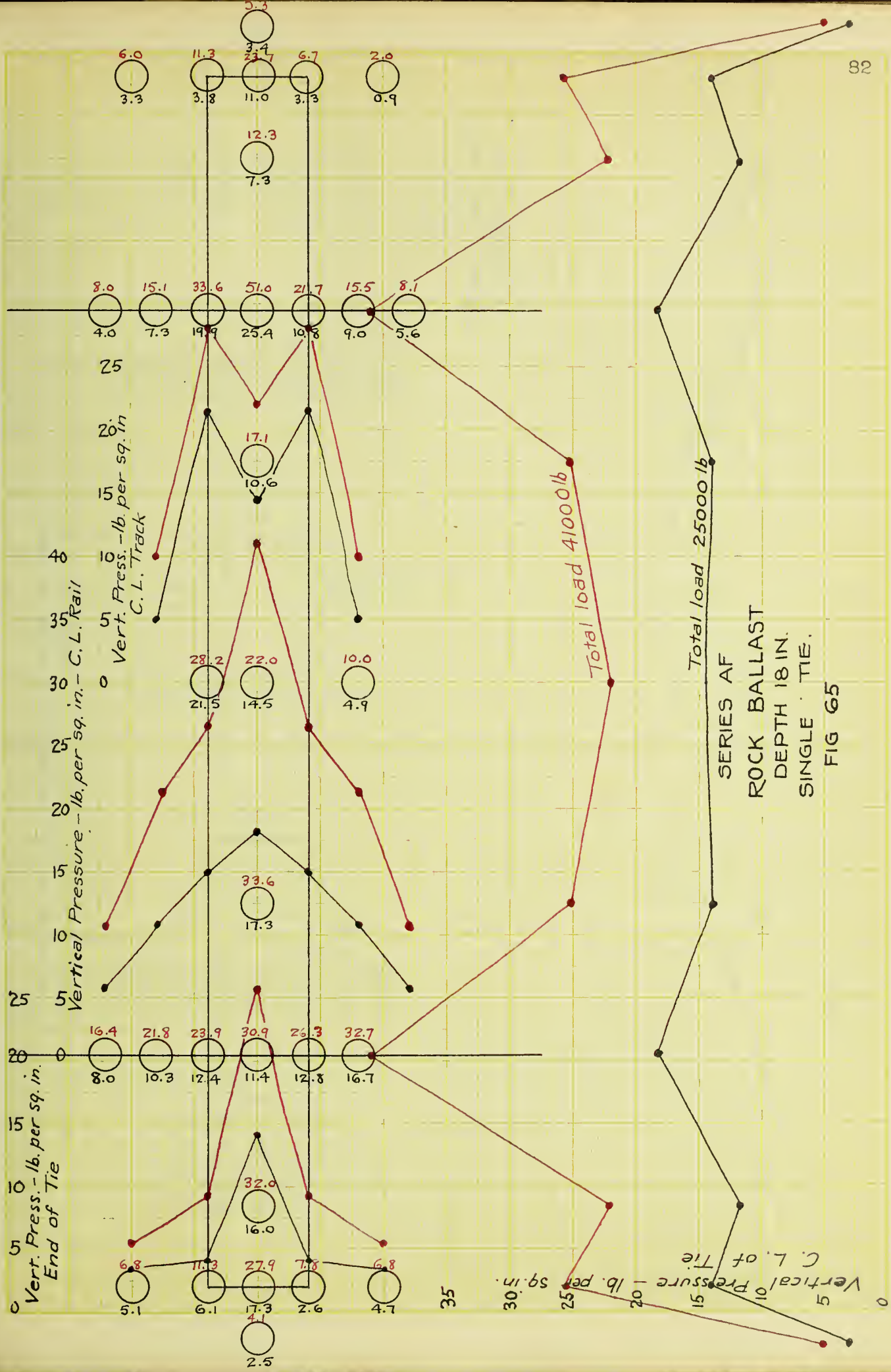
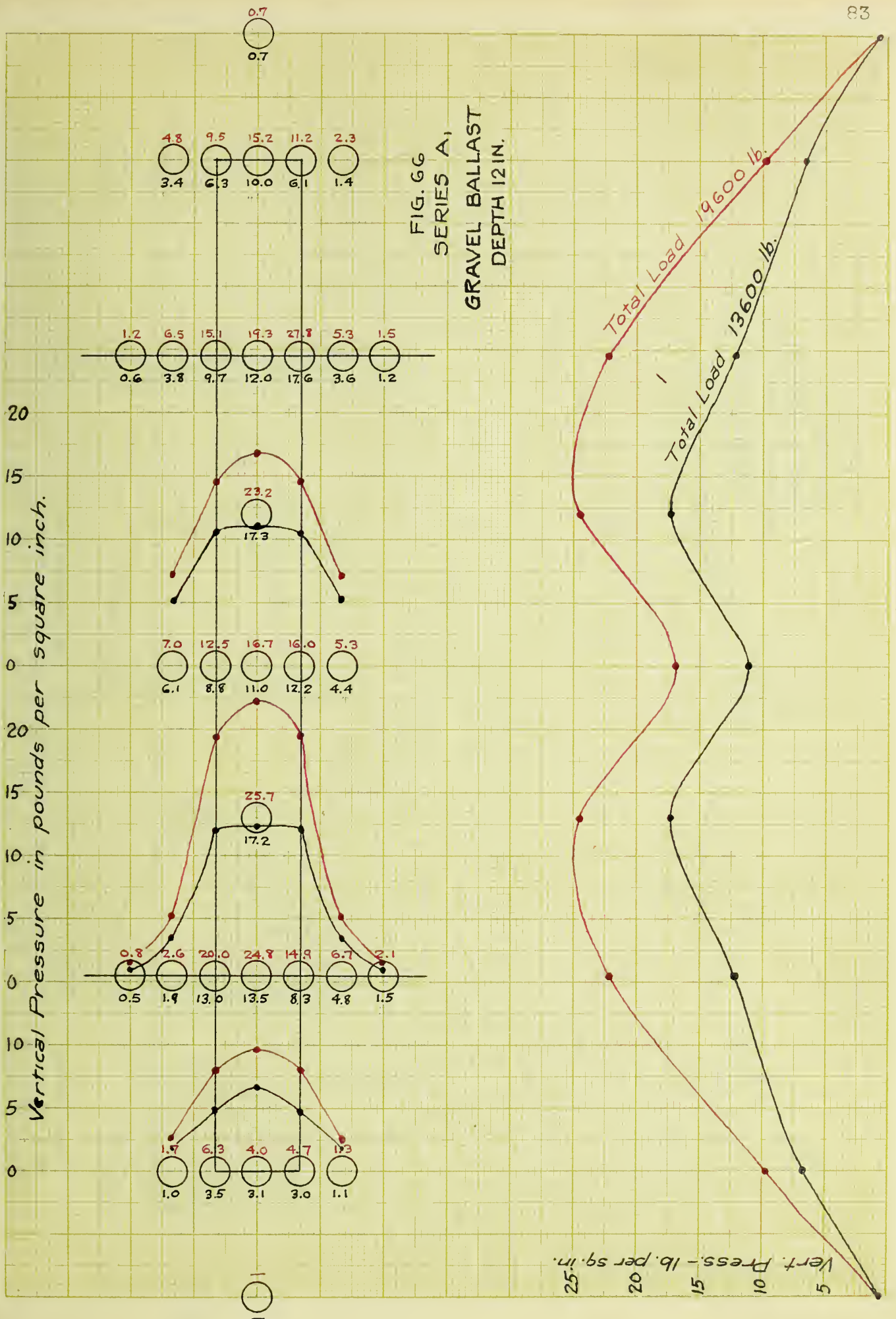
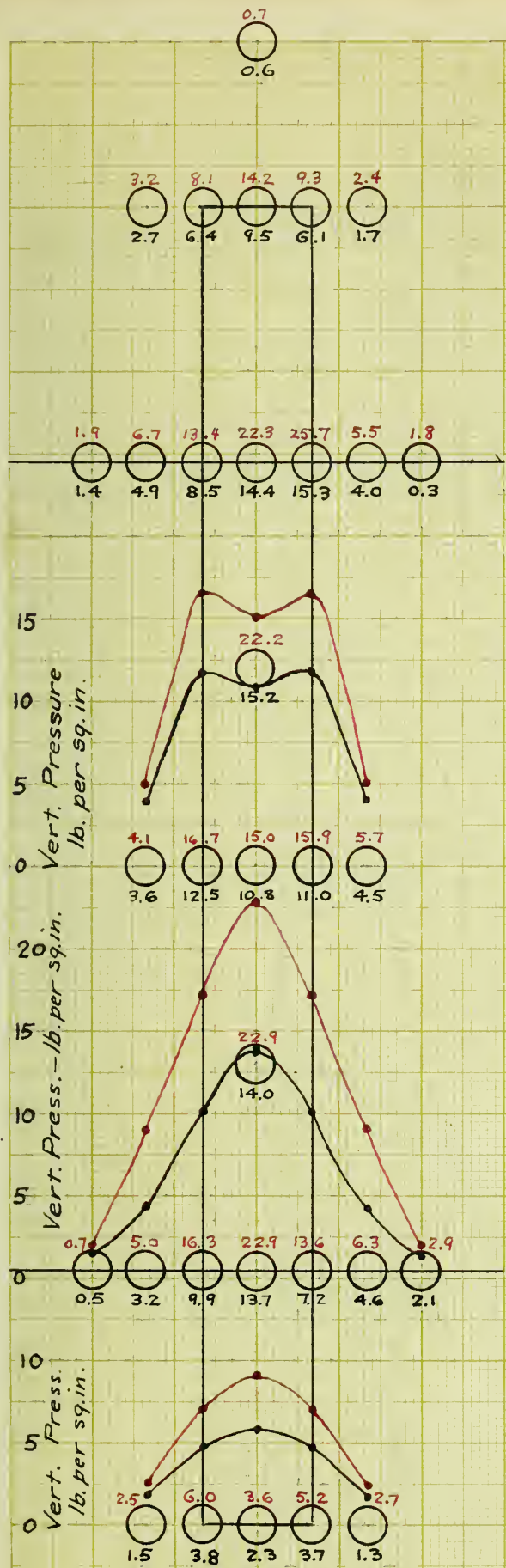


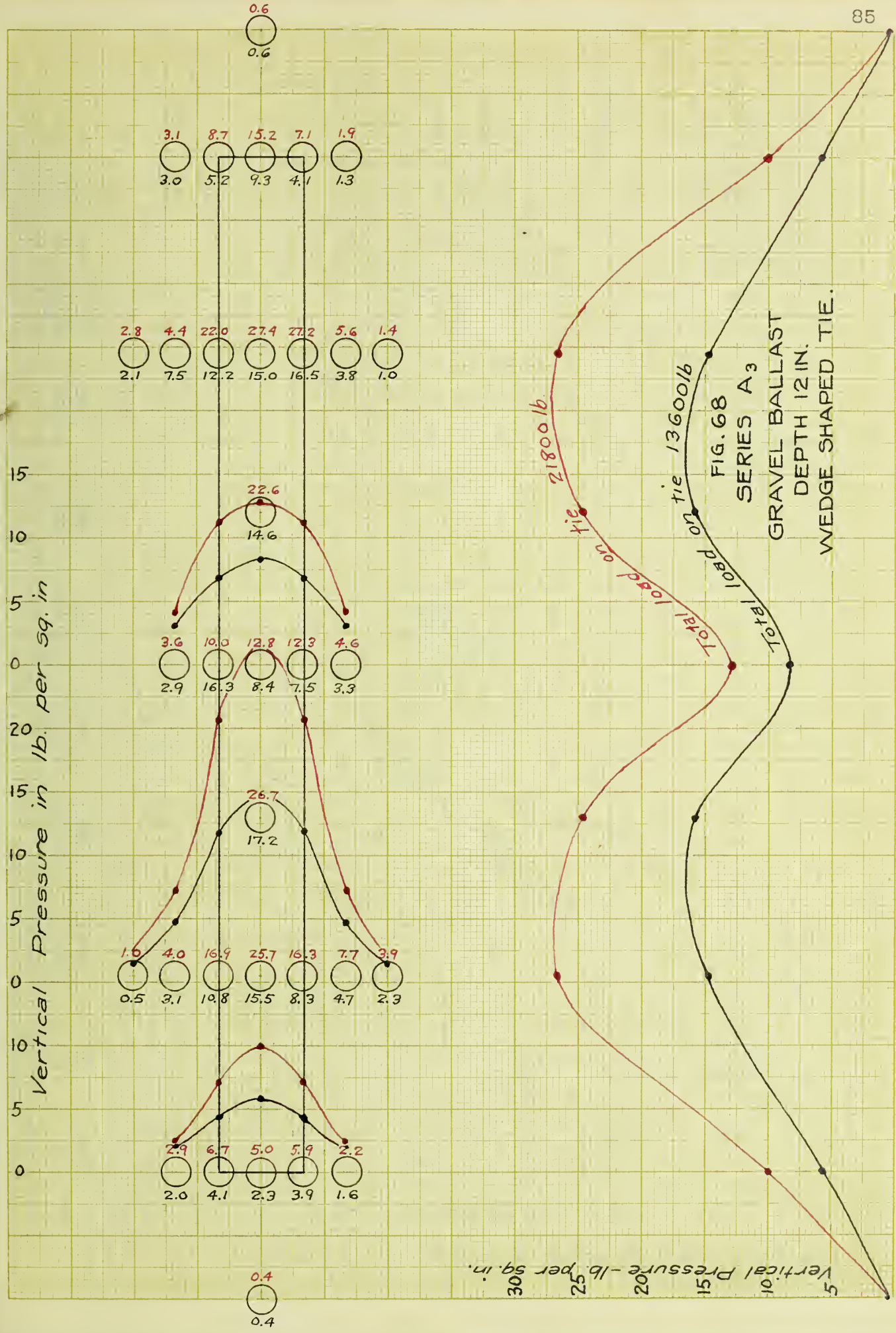
FIG. 66
SERIES A,
GRAVEL BALLAST
DEPTH 12 IN.





19600 lb
 Total Load
 13600 lb
 Total Load
 SERIES A₂
 GRAVEL BALLAST
 DEPTH 12 IN.
 SINGLE TIE.
 FIG. 67

Vertical Pressure - lb. per sq. in.





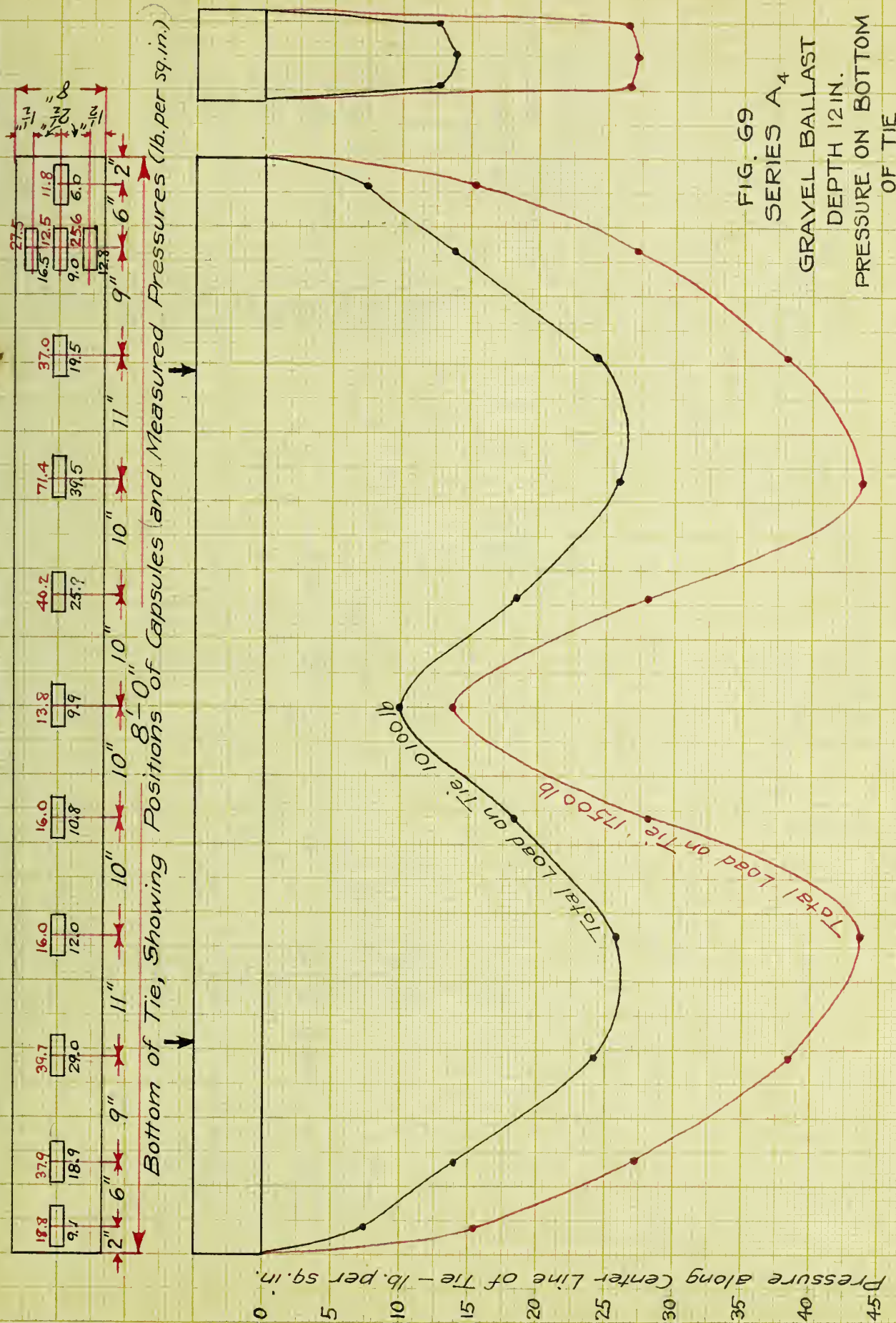
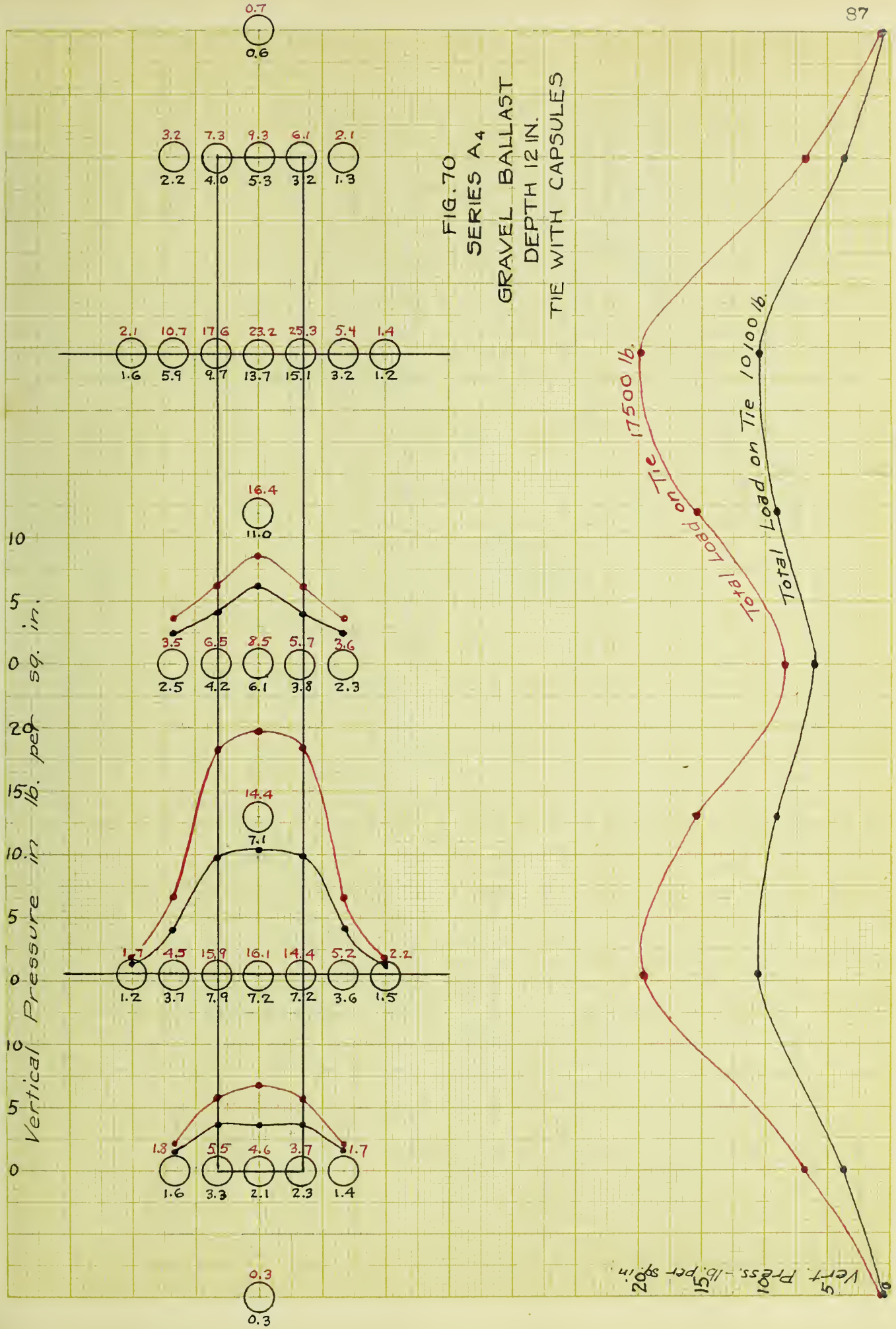
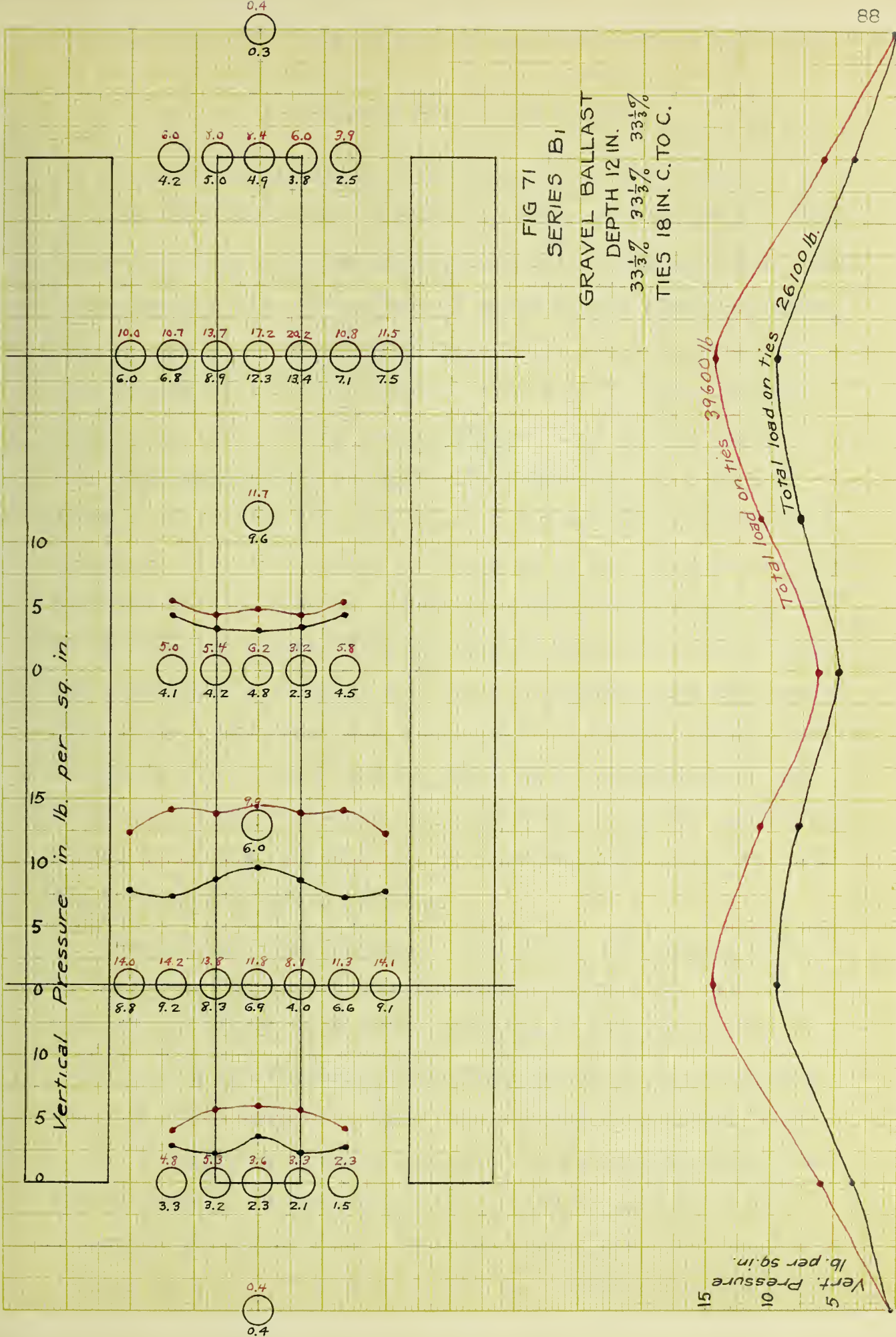




FIG. 70
SERIES A₄
GRAVEL BALLAST
DEPTH 12 IN.
TIE WITH CAPSULES





V. ANALYSIS OF RESULTS OF TESTS.

From an examination of the data and of the curves it will be seen that there are a number of factors which influence the intensity of pressure at any given point in the ballast. Among these factors are: the effect of tamping, the effect of blows, and the effect of the flexibility of the tie. In order to analyze the data it is therefore desirable to study average conditions, and to note the variations from the average.

Experiments with a Single Tie. In order to obtain an average of the results, the pressures measured by capsules at the same distance from the center line of the tie were averaged. From the results a curve was drawn showing the average pressure at different distances from the center line of the tie. Lines representing the highest and lowest pressures measured, were also drawn. Such curves are shown for the single tie experiments in Fig. 79, 80, 81, 84 and 86 for depths of sand ballast of 6, 9, 12, 18 and 25 inches respectively; in Fig. 82 and 85 for 12 and 18 inches respectively of rock ballast; and in Fig. 83 for 12 inches of gravel ballast.

Two or More Ties Loaded. The average pressures obtained in the manner indicated above has been plotted for various loadings in Fig. 87 to Fig. 96 inclusive. A dotted line, indicated as the "superimposed pressure curve" has also been drawn in these figures. These lines represent the addition of the overlapping vertical pressure curves for the ties considered singly. In consideration of the variations to be expected, the superimposed pressure curves fit the experimental results very well, indicating that the vertical pressure at any

given point in the ballast may be considered to be the sum of the vertical pressures which would be caused at that point if each of the ties was considered separately. By means of this principle, which seems to be established by these experiments, it is possible to estimate the pressure which would be caused at any point in the ballast by other loadings and tie spacings.

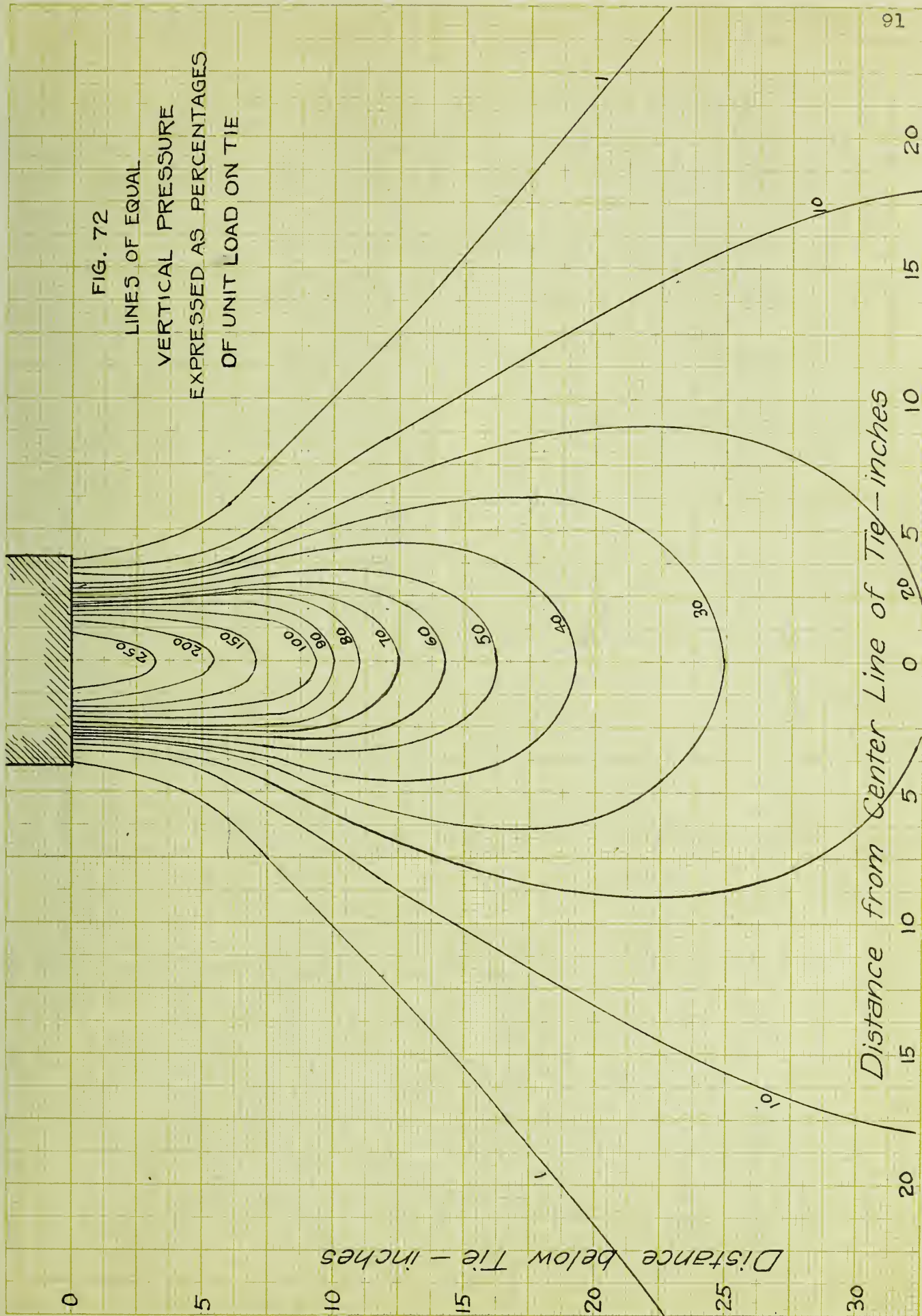
Comparison of Results with Sand, Rock and Gravel Ballast.

An examination of the average pressure curves for sand, stone and gravel ballasts of the same depth shows that there is little difference in the distribution of the pressure. The principal difference is that the distribution is more erratic in the case of the coarse ballasts. Of course the stone and the gravel ballasts will be displaced less by repeated loads accompanied by shocks, and for that reason make better material for ballast.

Contours of Equal Pressure. In Fig. 72 to 76 lines of equal vertical pressure have been drawn to show the pressure in the ballast beneath a single tie and beneath three ties under different loadings and with different tie spacing. The curves bring out clearly that a shallow ballast may concentrate rather than distribute the load on the tie. The use of 9 inches of rock ballast, for example, would not be expected to give good results, because the intensity of the pressure on the sub-grade directly below the tie will average 50% more than the average pressure on the tie. The result is that the ballast will be forced into the sub-grade and it will be necessary to supply more ballast to bring the track back to grade. When the depth of the ballast is about equal to the spacing of the ties it will be seen that the distribution of pressure on the sub-grade is quite uniform.

FIG. 72

LINES OF EQUAL
VERTICAL PRESSURE
EXPRESSED AS PERCENTAGES
OF UNIT LOAD ON TIE



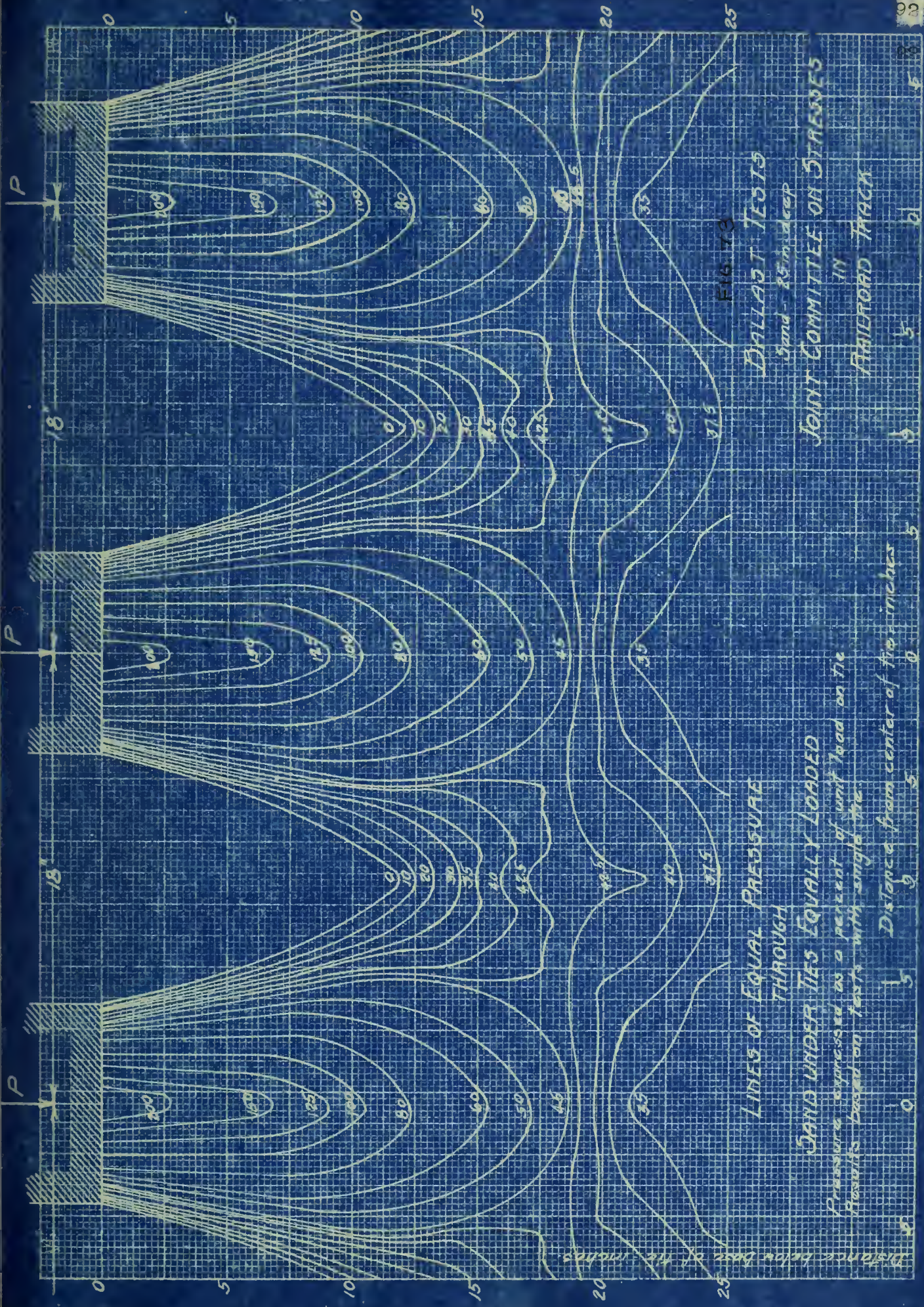


FIG. 73
DALLAST TESTS
Sand - 15 inches deep

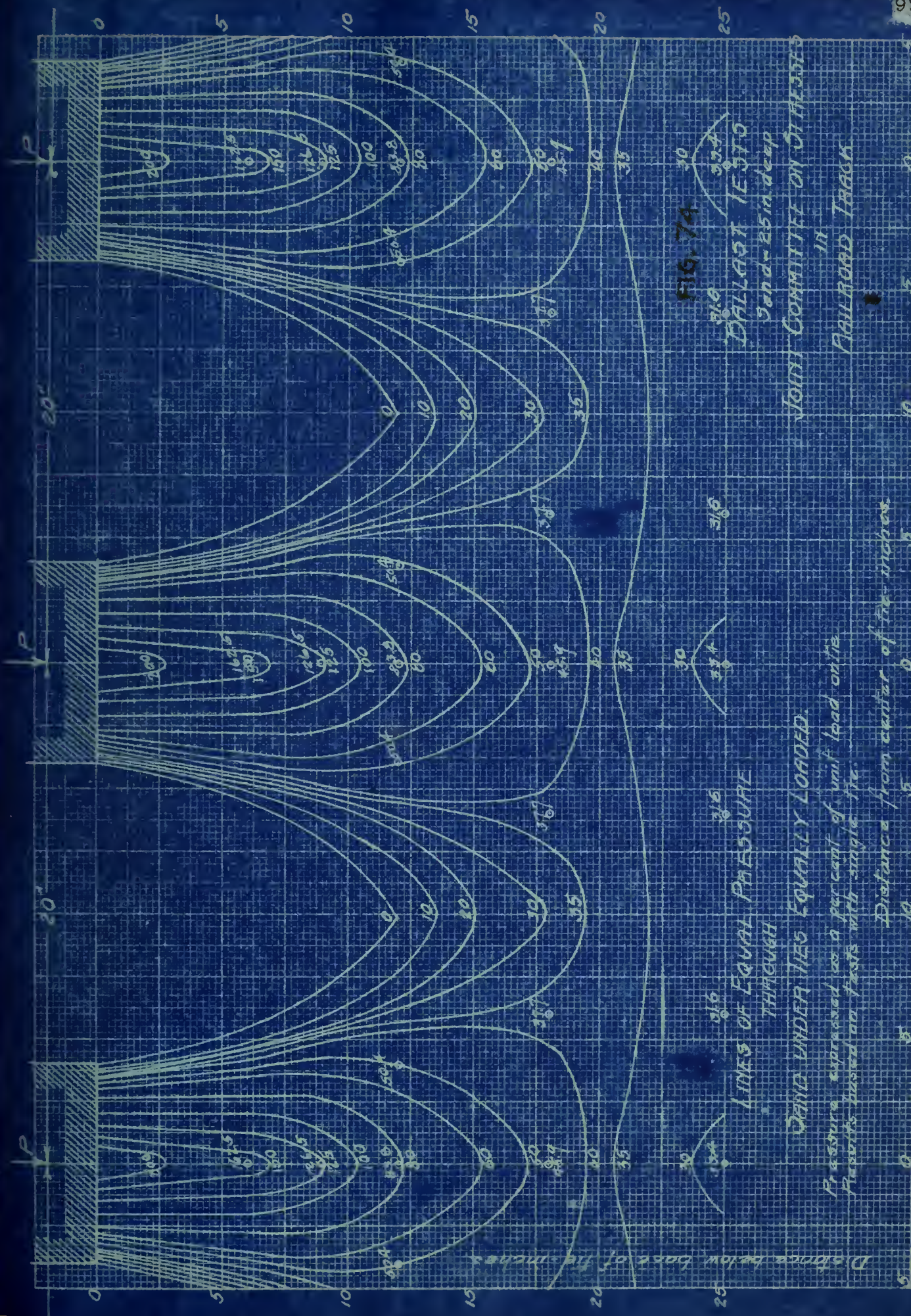
JOINT COMMITTEE ON STRAINES
IN
RAILROAD TRACK

LINE OF EQUAL PRESSURE
THROUGH

SAND UNDER TIES EQUALLY LOADED

Pressure expressed as a percent of unit load on tie
Results based on tests with single tie

Distance from center of tie, inches



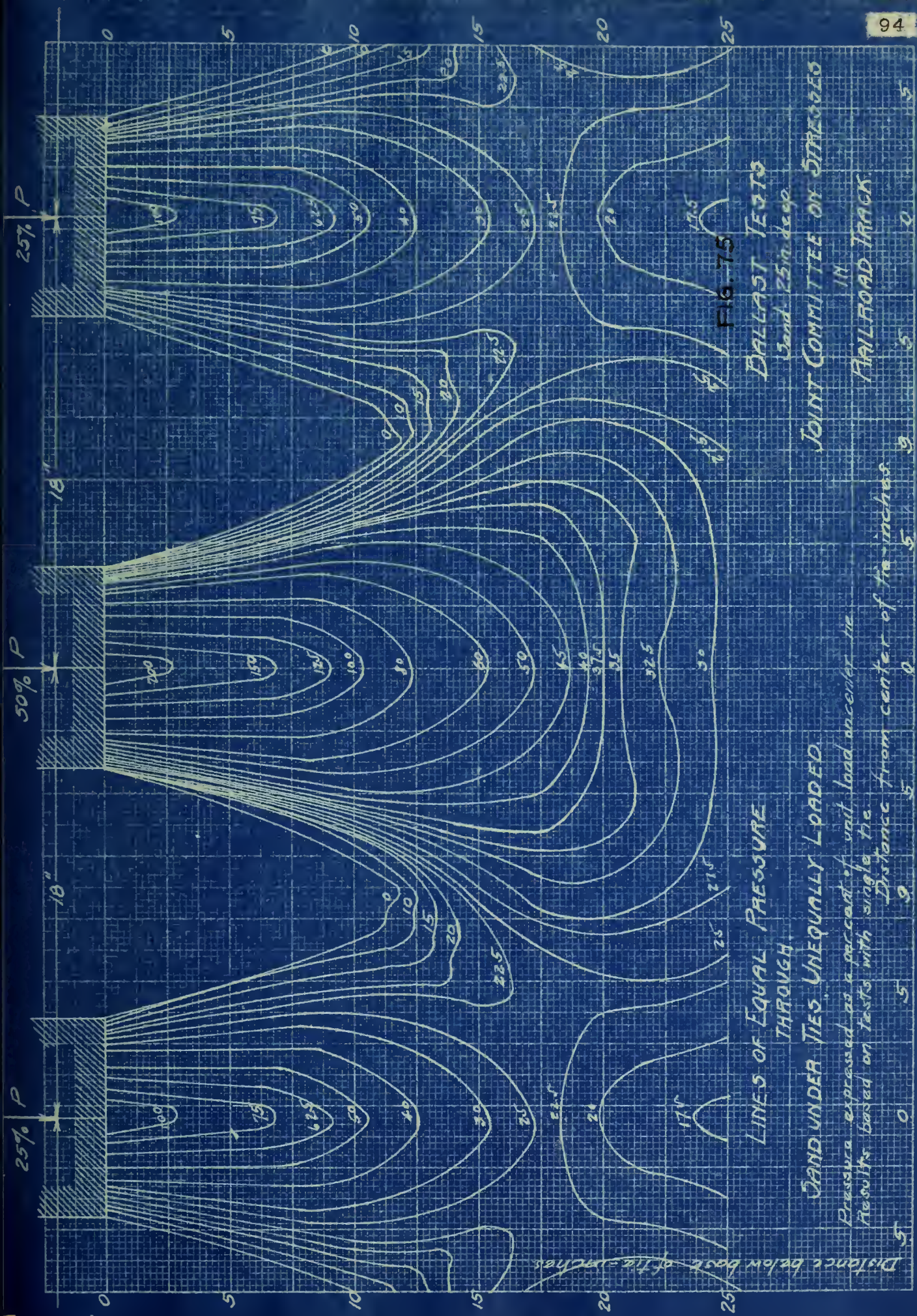
LINE OF EQUAL PRESSURE
THROUGH

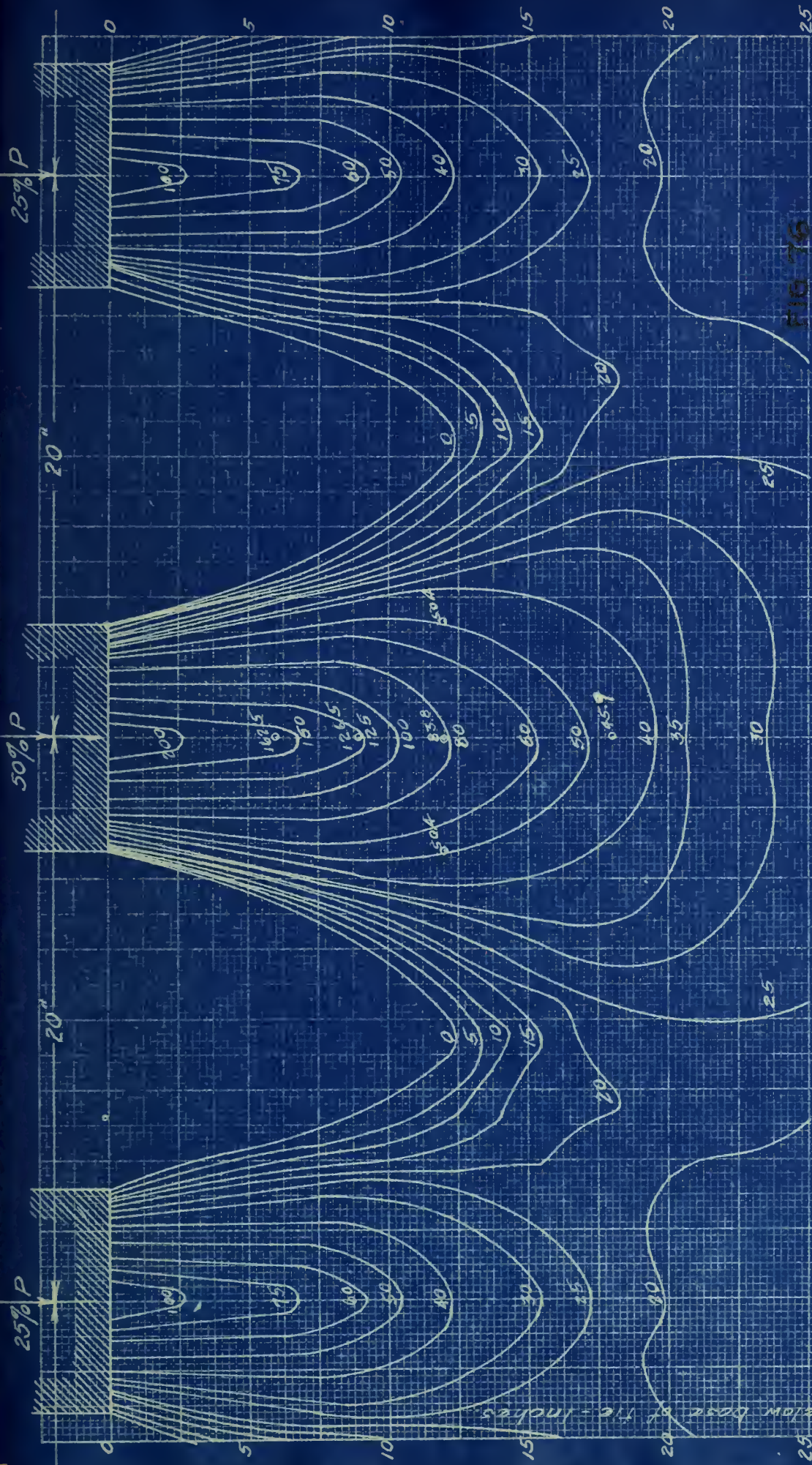
JOINT UNDER HAS EQUALLY LOADED.

Pressure expressed as a percent of unit load on the
results based on tests with angle 10°

Distance from center of the inches

Distance below base of the inches





LINES OF EQUAL PRESSURE THROUGH

SAND UNDER TIES UNEQUALLY LOADED

Pressure expressed as a percent of unit load on center tie. Results based on tests with single tie.

Distance from center of tie - inches

FIG 76

BALLAST TESTS

Sand - 25 in. deep

JOINT COMMITTEE ON STRESSES

IN RAILROAD TRACK

Intensity of Pressure Below Center Line of Tie. The distribution of the pressure below the center line of the tie is shown in the figures giving the results of the tests. The effect of the bending of the tie is shown by the variation of pressure in the ballast below the tie. If the tie were absolutely rigid the pressures would tend to be constant at any given depth below the center lined of the tie. The pressures are found to be least near the center line of the track and the greatest at points nearly vertically below the center line of the rail.

The effect of tamping is shown in some of the experiments to be to increase the pressures in the ballast below the part tamped. A somewhat wider distribution of the pressure is also obtained. In the maintenance of track the tamping is usually done a short distance on each side of the rails. The result of the tamping is therefore to increase the intensity of the pressure on the part of the sub-grade below the rails. Tamping the whole tie is not done because of the flexural stresses which may be caused in the tie.

The effect of blows on the tie while it is carrying load is to increase the pressures below the center line of the tie. The shock loosens the ballast near the edge of the tie, allowing it to flow laterally, in this way leaving a pillar of compacted ballast near the center line of the tie which carries most of the load.

The intensity of the pressure in the ballast below the center line of the tie also depends upon the load which is carried by the tie. Under the action of light loads there is little lateral displacement of the ballast under the tie. The

ballast under the tie is therefore almost equally compacted, and the pressures on the bottom of the tie are nearly uniform from one edge to the other. For heavier loads there will be a considerable flow of ballast in the lateral direction, with the result that the ballast near the edge of the tie is relatively loose and carries only a small part of the load.

Under service conditions the tie in a railroad track is subjected to heavy pounding loads. The conditions are therefore favorable for the development of high unit-pressures in the ballast directly below the center line of the tie, and for the development of high unit-pressures below the center of the rail. The pressures under the center of the tie determined by our experiments are therefore probably lower than the pressures developed under operating conditions.

In order to determine the relation between the unit-pressure below the center of the tie and the distance below the tie, the results of the experiments have been plotted on logarithmic paper in Fig. 77. Lines have been drawn to represent the average, the maximum and the minimum intensities of pressure. The average unit-pressure may be represented by the equation,

$$p_c = \frac{1680}{h^{1.25}}$$

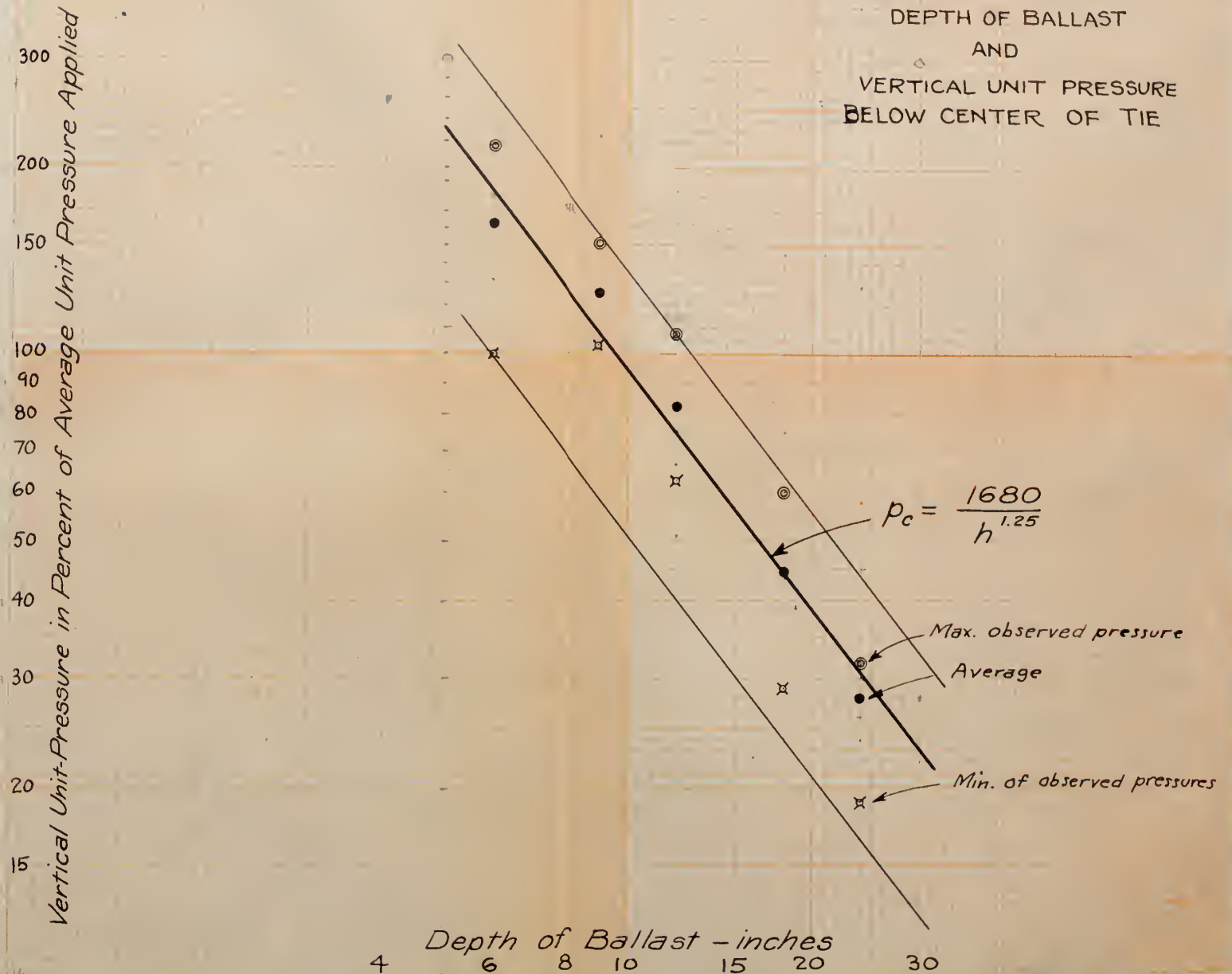
in which p_c is the pressure (expressed as a percent of the average unit pressure applied) at a distance h below the center line of the tie. The equation is purely empirical, but does represent the results quite well within the range of the tests, that is between 6 inches and 25 inches. The equation is found to apply to the pressures in rock ballast

FIG. 77
 RELATION BETWEEN
 DEPTH OF BALLAST.
 AND
 VERTICAL UNIT PRESSURE
 BELOW CENTER OF TIE

STANDARD TIE (10' x 10' x 10')



FIG. 77.
RELATION BETWEEN
DEPTH OF BALLAST
AND
VERTICAL UNIT PRESSURE
BELOW CENTER OF TIE



and in gravel ballast. For depths less than 6 inches the equation gives results which are too high. The pressure on the bottom of the tie, that is, when $h = 0$, is infinite according to the equation - an absurd result. The greatest intensity of pressure on the tie is shown to be less than 200% of the average unit-pressure in the experiments summarized in Fig. 69. In some experiments on sand ballast the pressure was measured by a capsule on the center line of the tie and directly below the rail. The highest pressure measured by this capsule was 279% of the average unit-pressure. It was also shown that the intensity of the pressure depended upon the load on the tie. In one of the experiments the pressure was 203% of the average unit-pressure on the tie when the load on the tie was 10,000 lb., was 276% of the average when the load on the tie was 16,670 lb., and when the load had been released to 10,000 lb. it was 253% of the average.

The foregoing discussion indicates that the empirical equation for the pressure at various depths below the center of the tie, will not give good results for depths much less than 6 inches. The equation will probably give fairly good results for depths up to 40 inches.

The Horizontal Component of the Pressure. In the preceding discussion reference has been made to the lateral movement of the ballast due to the horizontal forces. According to the Rankine analysis of the pressures in a granular mass, the maximum and the minimum pressures at any point are at right angles to each other, and the ratio of the maximum pressure to the minimum pressure cannot exceed the amount

$$\frac{1 + \sin \phi}{1 - \sin \phi}$$

in which ϕ is the angle of friction, and is usually taken as the angle of repose of the material.

At the edge of the tie the minimum pressure is horizontal and its magnitude depends upon the restraint which the ballast offers to lateral movement. The vertical unit-pressure near the edge of the tie cannot be more than

$$\frac{1 + \sin \phi}{1 - \sin \phi} P_h$$

P_h being the maximum horizontal unit-pressure which can be developed. An attempt to put a greater vertical pressure on the ballast at this point causes lateral movement. In some of the earlier experiments the lateral movement of the ballast was shown by radial lines scratched on the cast iron plate. As the center of the tie is approached the horizontal pressures increase rapidly, permitting greater vertical pressures to be applied.

It is evident that the load which a tie can carry without causing lateral movement in the ballast depends upon the coefficient of friction. Broken stone ballast has a coefficient of friction of about 1.00, which corresponds to an angle of friction of 45 degrees. Sand ballast has a coefficient of friction of about 0.67, corresponding to an angle of friction of about 34 degrees. Substituting in Rankine's formula,

$$P_{\max} = 5.7 P_{\min} \text{ for broken stone ballast, and}$$

$$P_{\max} = 3.54 P_{\min} \text{ for sand ballast.}$$

The capacity for carrying load without heaving between ties varies as the square of the coefficients, or in the case of

the broken stone and the sand ballasts as 26 : 10. In the case of broken stone ballast, however, the load which it can sustain depends upon the carrying capacity of the sub-grade and not upon the load which will cause the ballast to heave.

The experiments in Series T1, T3, T4 and T5 were made to determine what effect the depth of ballast around the tie would have on the distribution of the vertical pressures on a horizontal plane 12 inches below the bottom of the tie. For the pressures used in these experiments it seems to make little difference in the distribution of pressure whether the tie rests on top of the ballast or if the ballast is flush with the top of the tie.

Experiments with Wedge Bottom Tie. A few experiments were made with a tie with a wedge shaped bottom. The point of the wedge was 1.5 inches lower than the side of the tie. The results of the experiments are shown in Fig. 55 and 56. A comparison of the results with the experiments of Series R and T1 shows a very marked difference in the distribution of the pressure for the same loads and depth of ballast. The center pressure under the wedge shaped tie is lower and the pressure is more uniformly distributed.

Series A3 consisted of experiments on the wedge bottom tie with 12 inches of gravel ballast. The results do not differ from the experiments on the flat tie of Series A2 in such a marked manner as in the case of experiments on sand ballast.

Since pole ties can easily be made with wedge bottoms it is recommended that further experiments be made along this line. Different angles of wedge should be tried out.

Effect of Repeated Loadings. The ballast used in the experiments was in a soft condition. That is, it had been loaded only a few times. In order to determine the effect of the repetition of load on the distribution of the pressure and on the settling of the ties, a series of experiments was run using three ties on 18 inches of sand ballast. The middle tie carried twice as much load as the outside ties. Load was applied to the ties 300 times and readings were taken of the pressure capsules and of the vertical movement of the middle tie.

The distribution of the vertical pressures is shown in Fig. 97 and 98 giving the average pressures found in the first 163 loadings and in the loadings from 164 to 300, respectively. It will be noted that there is a difference, due no doubt to the lateral flow of the ballast. A comparison of the average pressures ^{are} given in Fig. 99. It will be seen that the distribution was quite uniform at the beginning, but that after the load had been applied a number of times there was a considerable redistribution of the load.

The vertical movements of the ends of the tie, the center of the tie and at a distance of 15 inches from the end are shown in Fig. 100, 101, and 102. The upper curve represents the lowering of the tie from the beginning of the experiments while under the action of the load. The lower line represents the total lowering from the beginning of the test when the load has been removed. The lower line represents the permanent depression of the tie. It will be noted that the lines are about the same distance apart at all times. This fact

is shown more clearly in Fig. 103, in which the elastic depression of the tie fifteen inches from the end is shown for the different loadings. It will be noted that the elastic depression of the tie at this distance from the end of the tie averages about 0.125 inches, and that it does not vary greatly from this value.

Hysteresis Curves For Sand. In Fig. 104 the load-depression curves for the ends of a tie on 14 inches of sand ballast are shown. The first loading produces very great permanent depression. When the load is removed the deformation continues. This has been noticed in all of the experiments, the deformation either increases as the load is taken off, or decreases very little. When the load is nearly all removed, there is a great decrease in the depression, due to the back-lash of the tie.

Theoretical Analysis of the Distribution of Pressure.

Pressures are transmitted through non-cohesive materials by means of the pressure exerted by each grain upon its neighbors.

In order to reduce the analysis to its simplest form it will be assumed that the ballast consists of incompressible cylinders of uniform size, piled in the most compact manner, and having their geometric axes parallel to the tie. It will also be assumed that there is sufficient lateral restraint to prevent any of the cylinders from moving horizontally. Each cylinder rests on two cylinders as shown in Fig. 78. Beginning with a vertical pressure of 2048 on the upper cylinder of the pile, the vertical component of the pressure on each of the cylinders below it will be 1024. Proceeding to the third row, each cylinder receives one-half of the vertical pressure on the cylinders which rest on it. The vertical pressure carried by

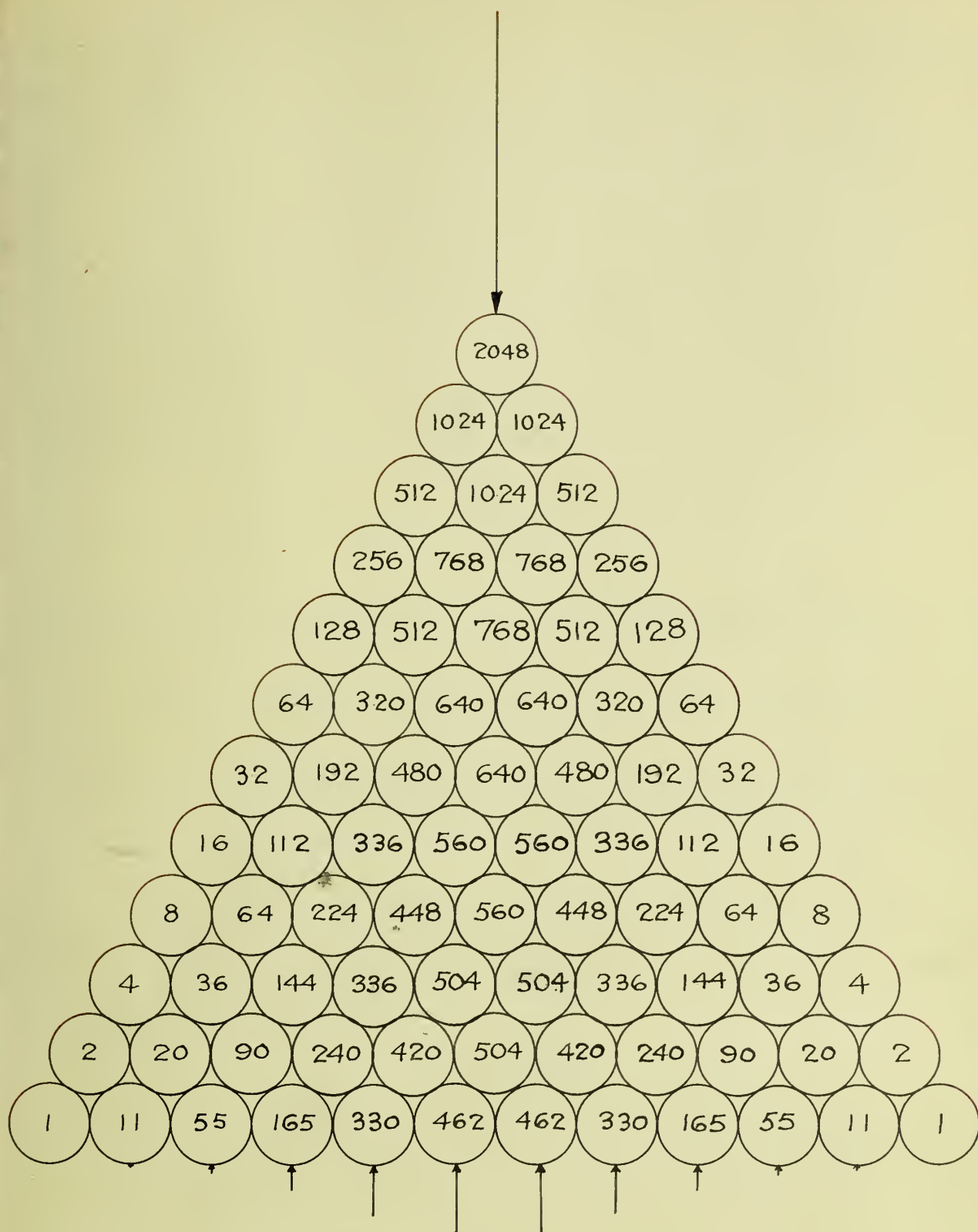


Fig. 78 Distribution of Vertical Pressure in a Pile of Cylinders

the outside cylinders is therefore 512, and since the middle cylinder receives two loads of 512 it will carry a total vertical pressure of 1024. Proceeding in this manner the pressure carried by the cylinders will be as indicated in the figure. Arrows have been drawn indicating the magnitude of the vertical forces on the bottom row of cylinders. It will be seen that the magnitude of the pressure decreases as the distance away from the line of action of the load increases. It has been found by trial that the distribution of the vertical pressures at any depth is represented by the equation

$$p = \frac{\frac{p_c}{10}}{\frac{p_c^2 x_1^2}{10 \cdot 7220}}$$

in which p = vertical unit-pressure on a horizontal plane at any distance x from the line of action of the load.

p_c = vertical unit-pressure on the line of action of the load, at the same depth.

x_1 = distance from the action line of the load expressed with the width of the loaded area as the unit. If an 8-in. tie is used, x_1 will be expressed in units of 8 inches; that is, when $x_1 = 2$ the distance is 16 inches.

It has been shown that the vertical unit pressure on the line of action of the load at any depth h below the tie may be found from the equation:

$$p_c = \frac{1680}{h^{1.25}}$$

Letting $x_1 = x/8$ and substituting the value of p_c in the equation for the distribution of pressure,

$$p = \frac{\frac{1680}{h^{1.25}}}{10 \frac{6.13 x^2}{h^{2.5}}}$$

In order to compare the results from this equation with the experiments, curves representing the results from the experiments have been plotted in red in Fig. 79 to 86. It will be seen that the agreement is quite good. The equation is based upon the results of experiments with depths of ballast ranging from 6 to 25 inches. There is therefore an uncertainty as to its use outside of these limits. In the opinion of the writer, extrapolation would give good results for depths up to 40 inches, but would probably give poor results for depths less than 6 inches.

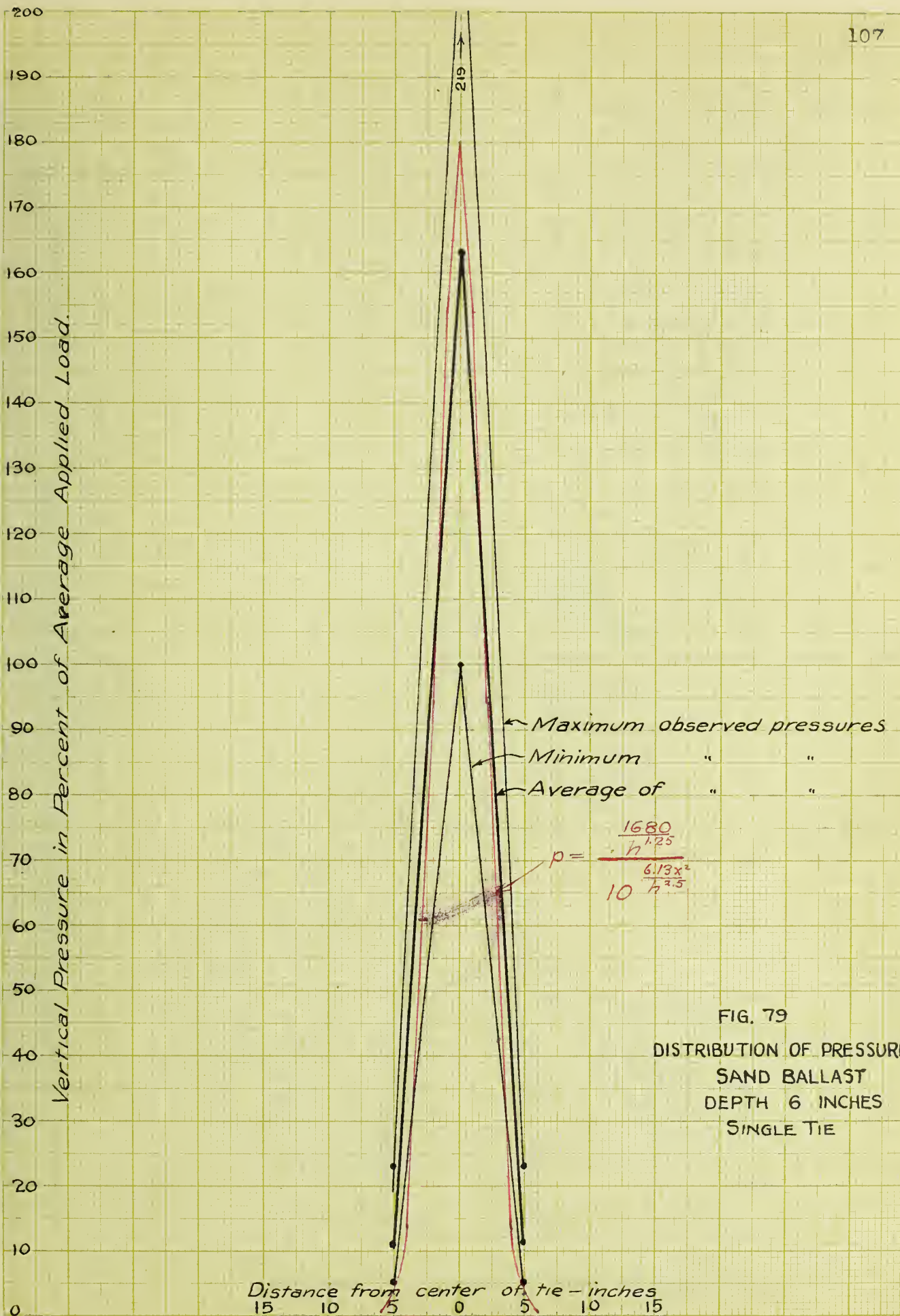


FIG. 79
DISTRIBUTION OF PRESSURE
SAND BALLAST
DEPTH 6 INCHES
SINGLE TIE

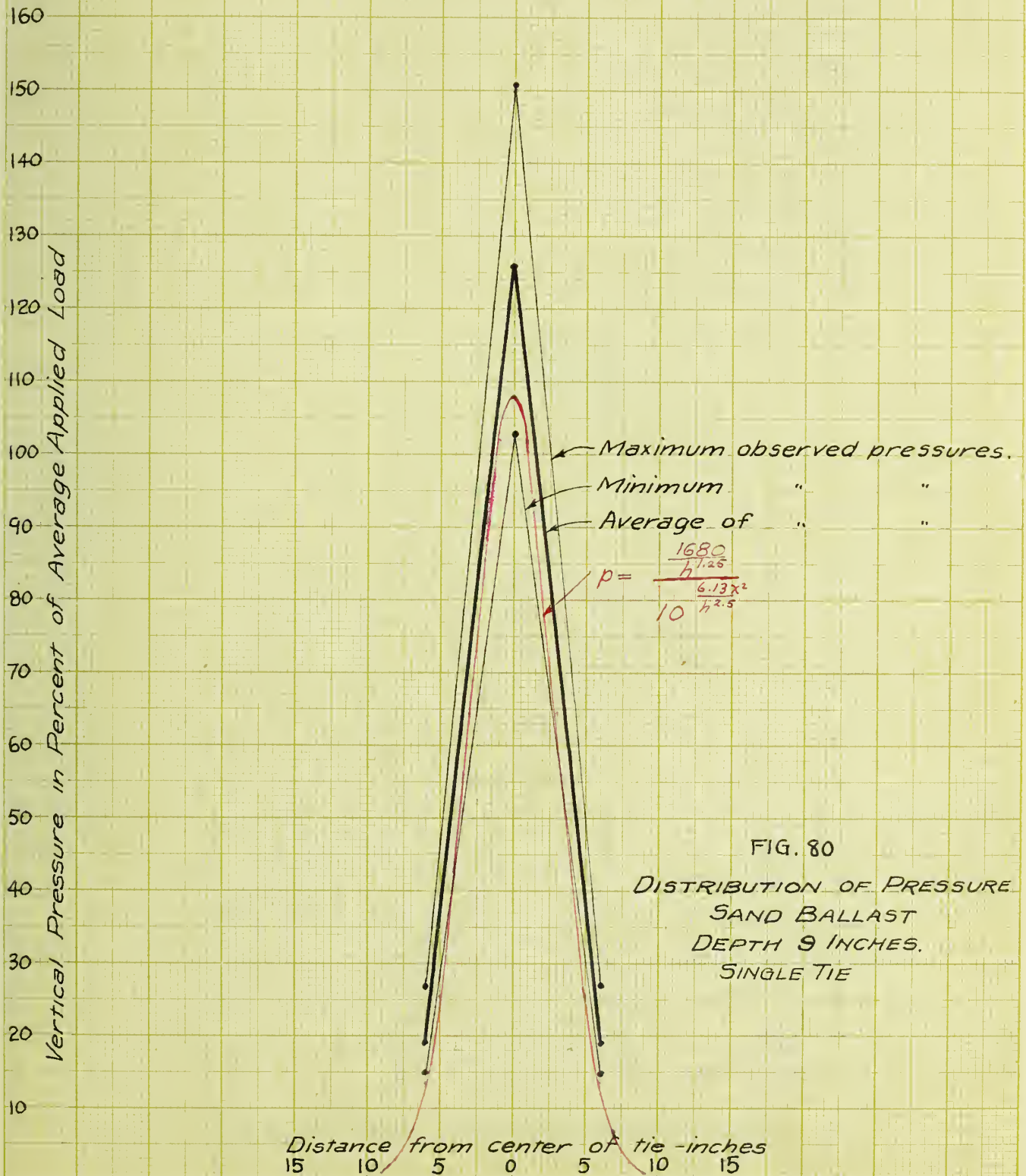
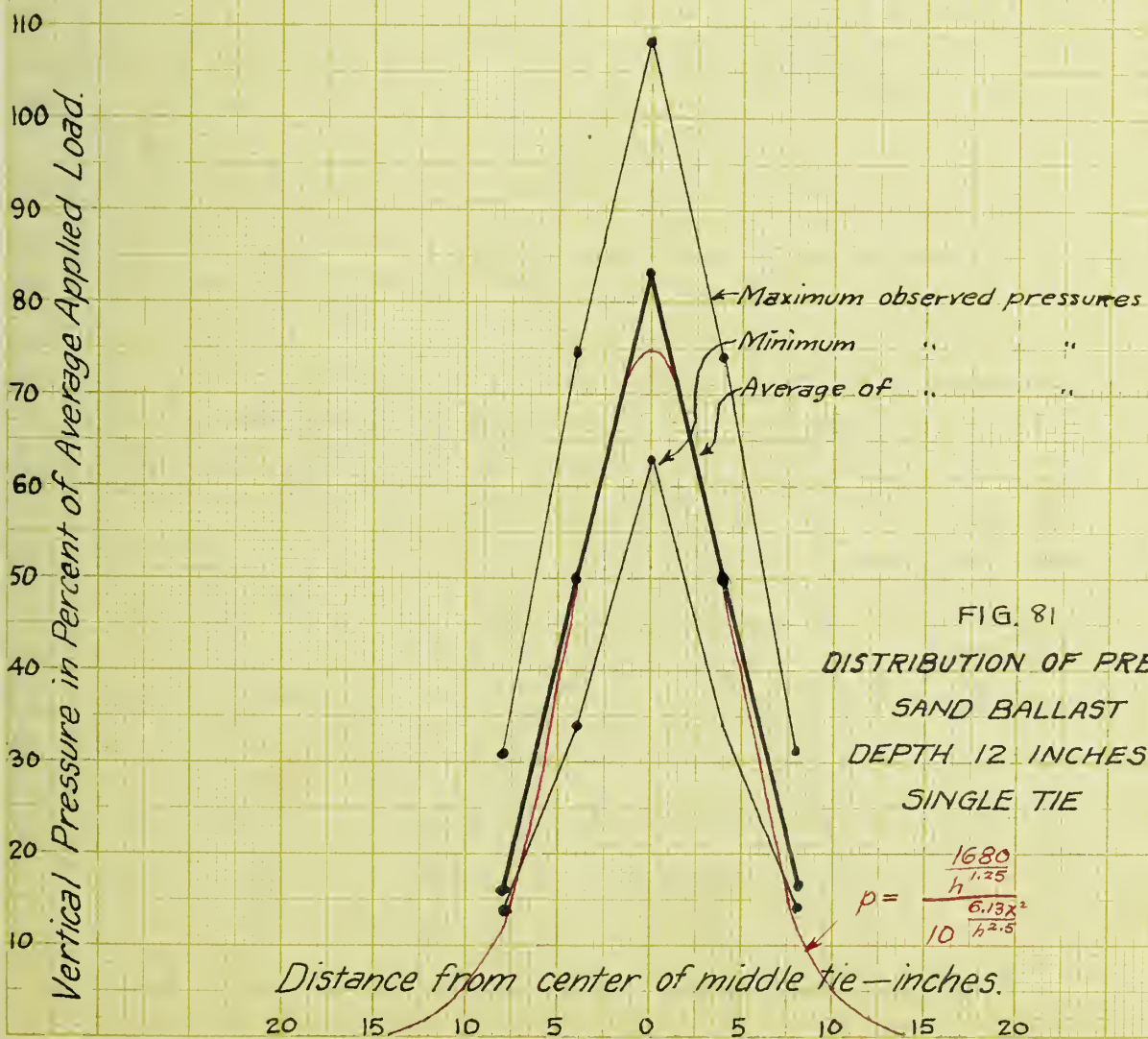
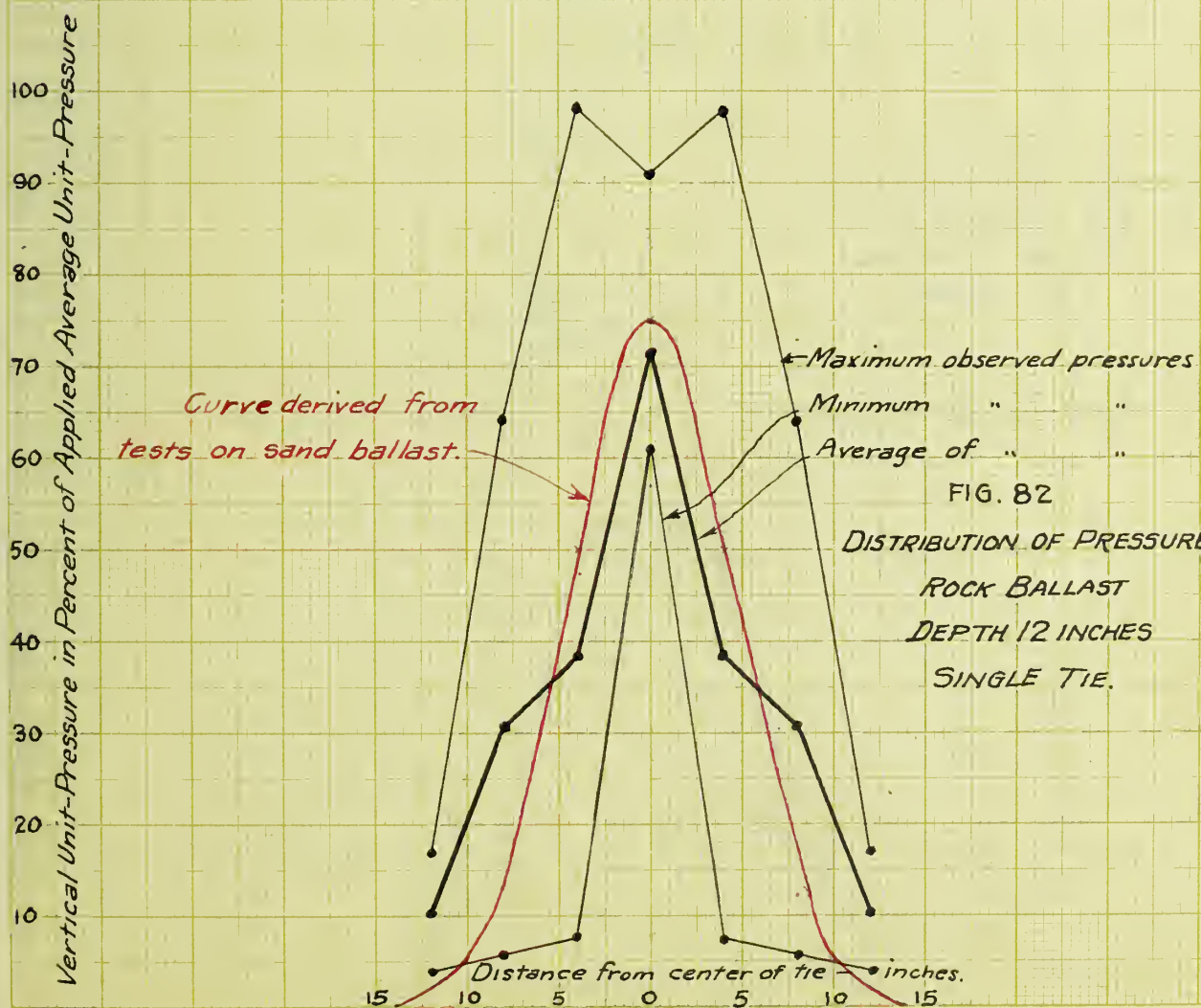
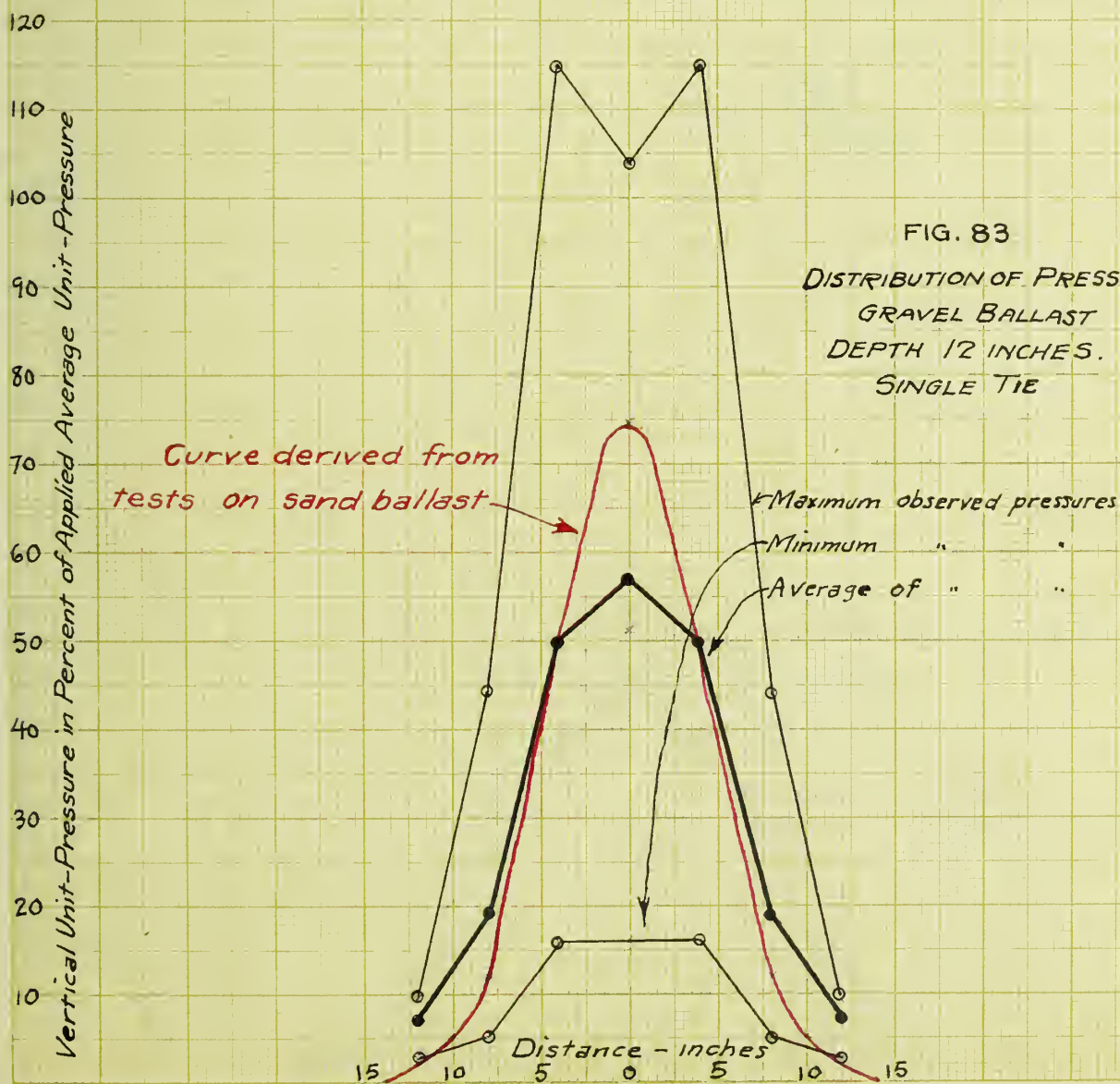
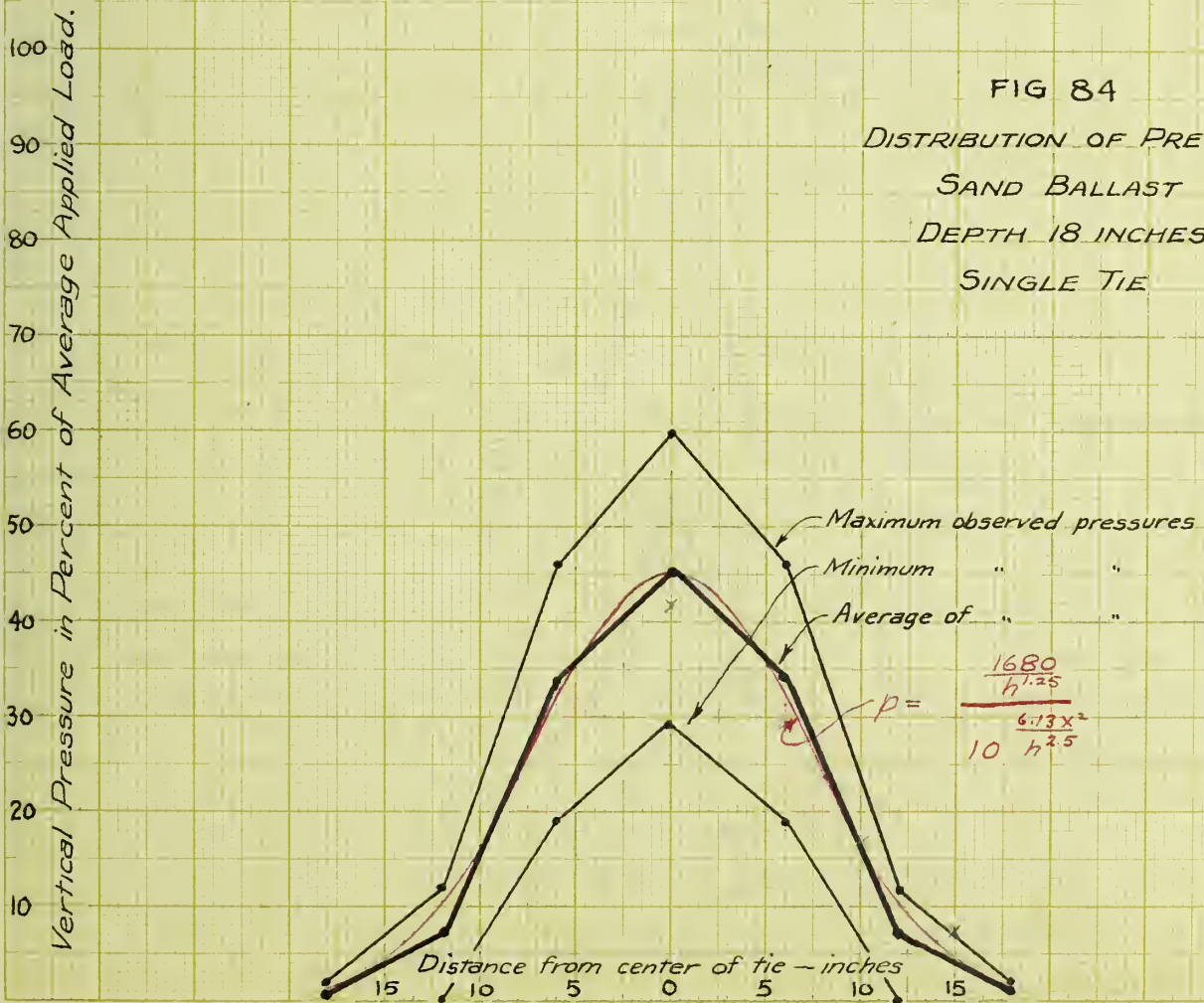


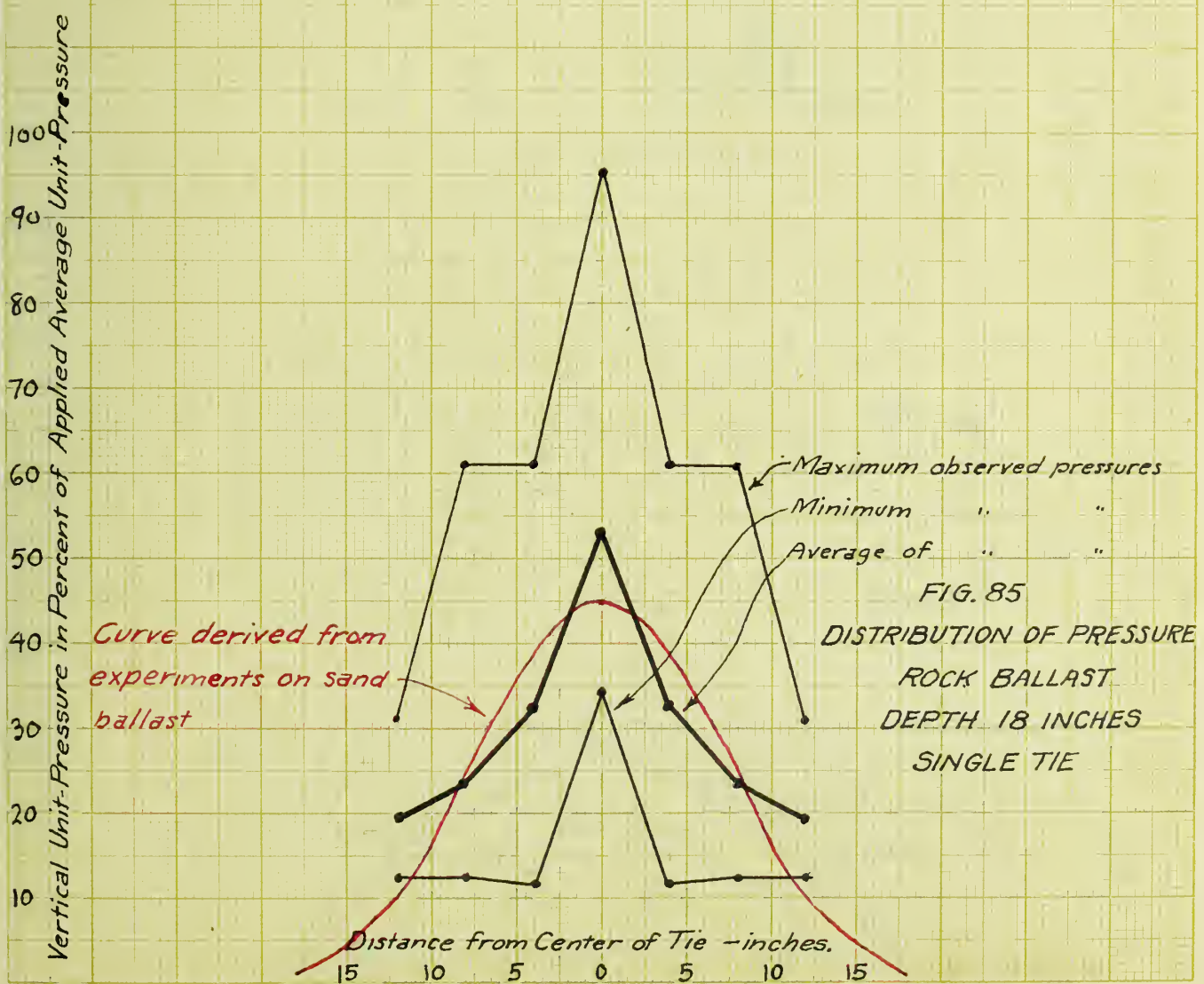
FIG. 80
DISTRIBUTION OF PRESSURE
SAND BALLAST
DEPTH 9 INCHES.
SINGLE TIE

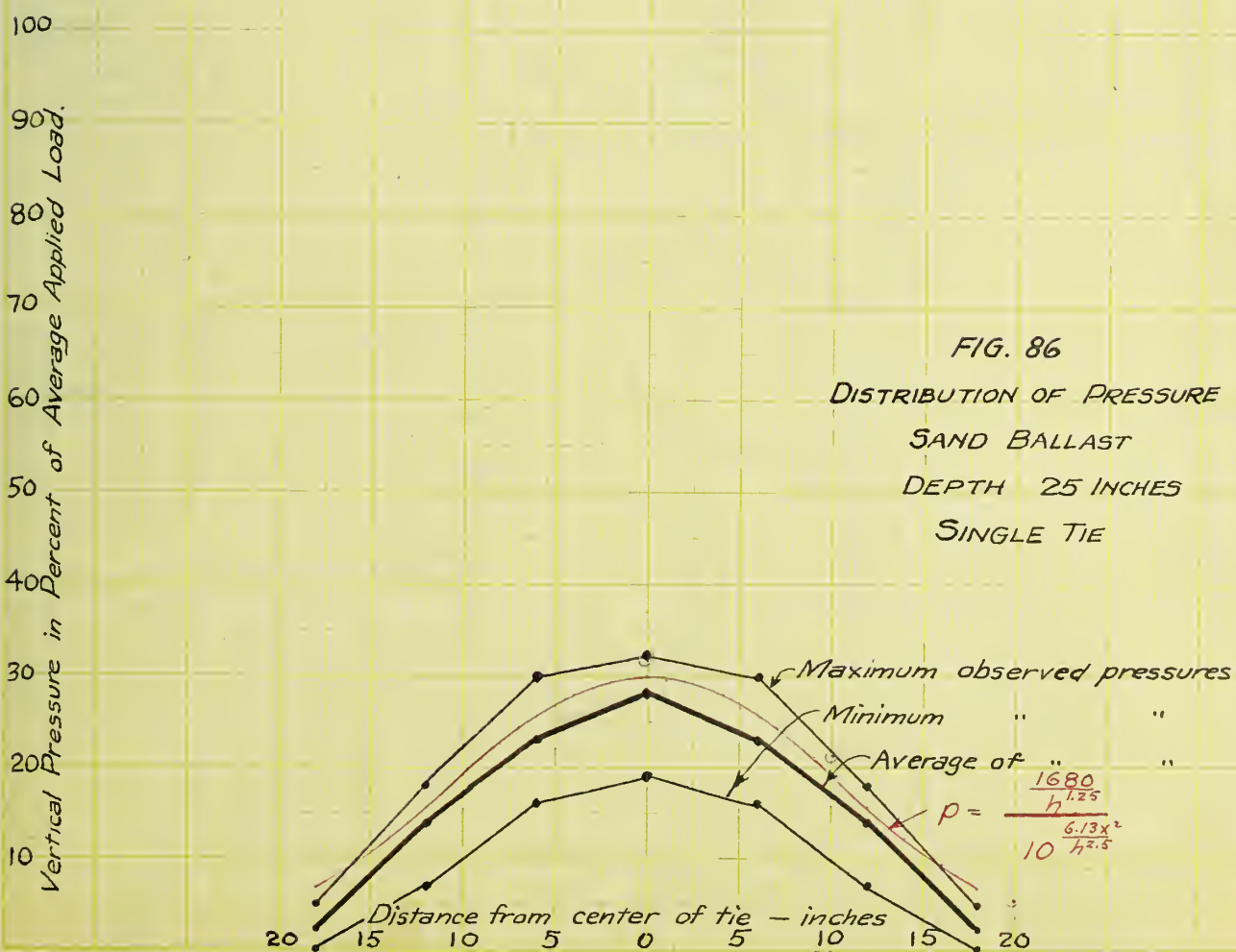












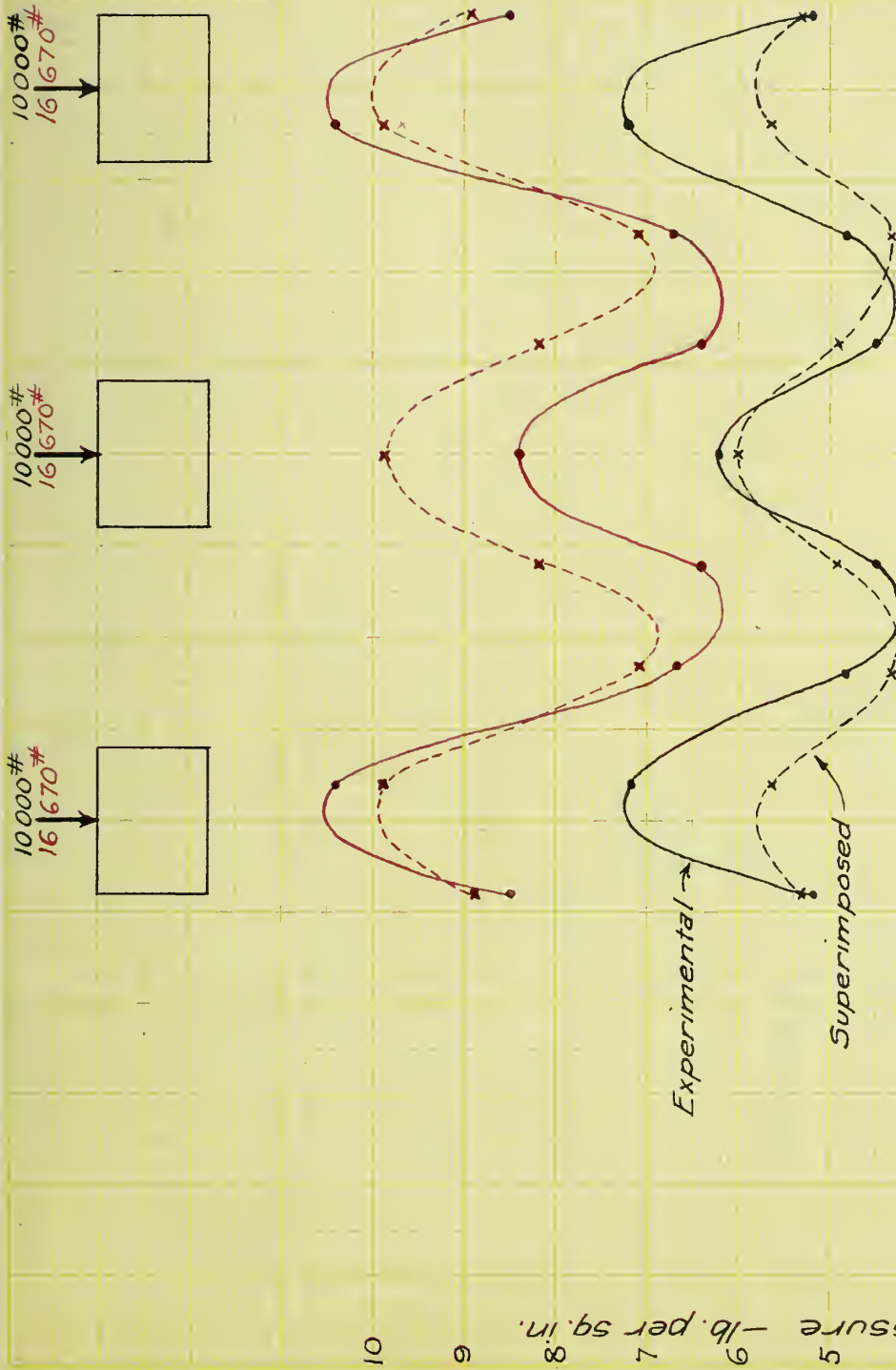


FIG. 87
AVERAGE PRESSURE CURVES
SAND BALLAST
DEPTH 18 INCHES
SERIES H

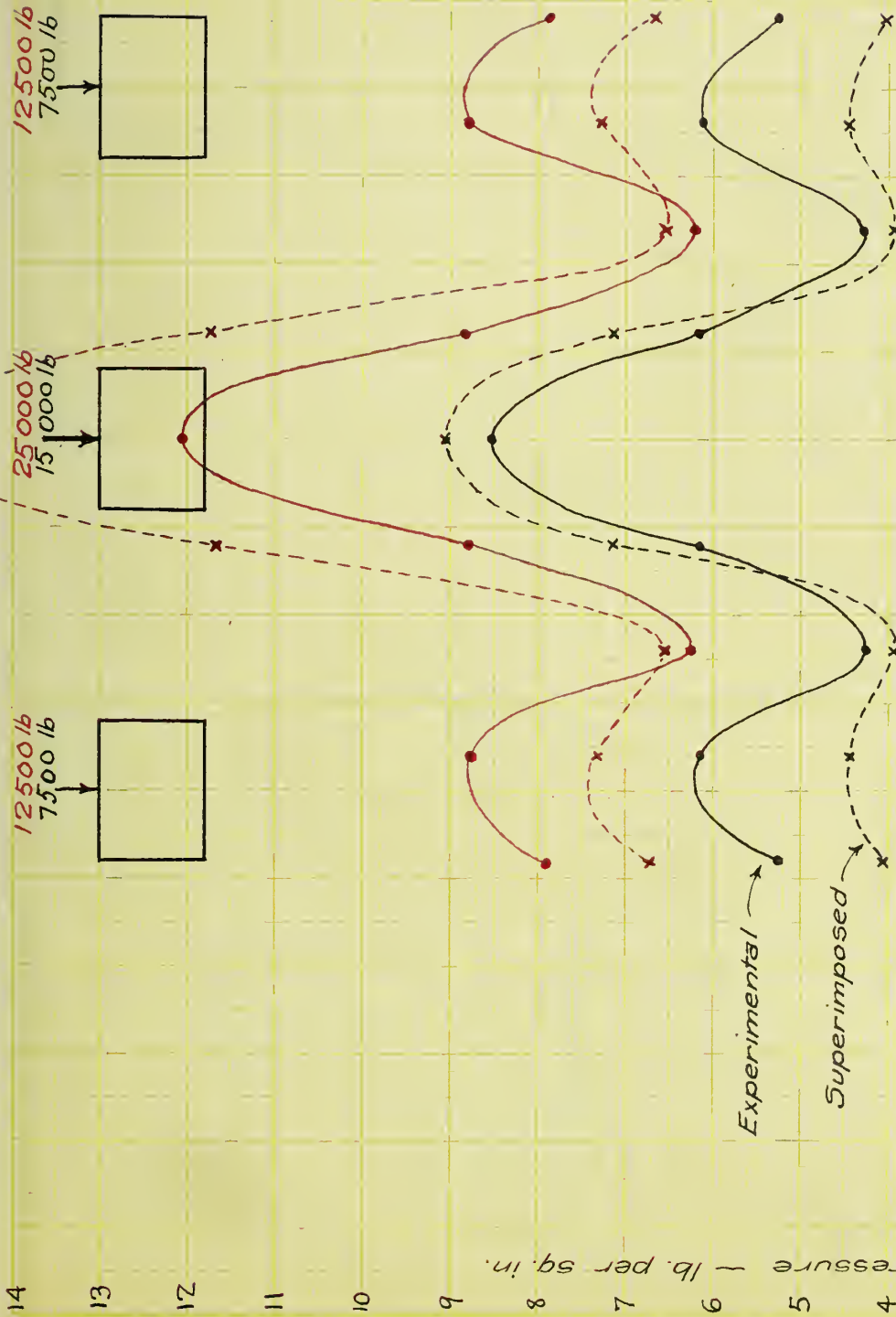


FIG. 88
AVERAGE PRESSURE CURVES
SAND BALLAST
DEPTH 18 INCHES
SERIES I

Distance from center line of middle tie — inches.

30

30

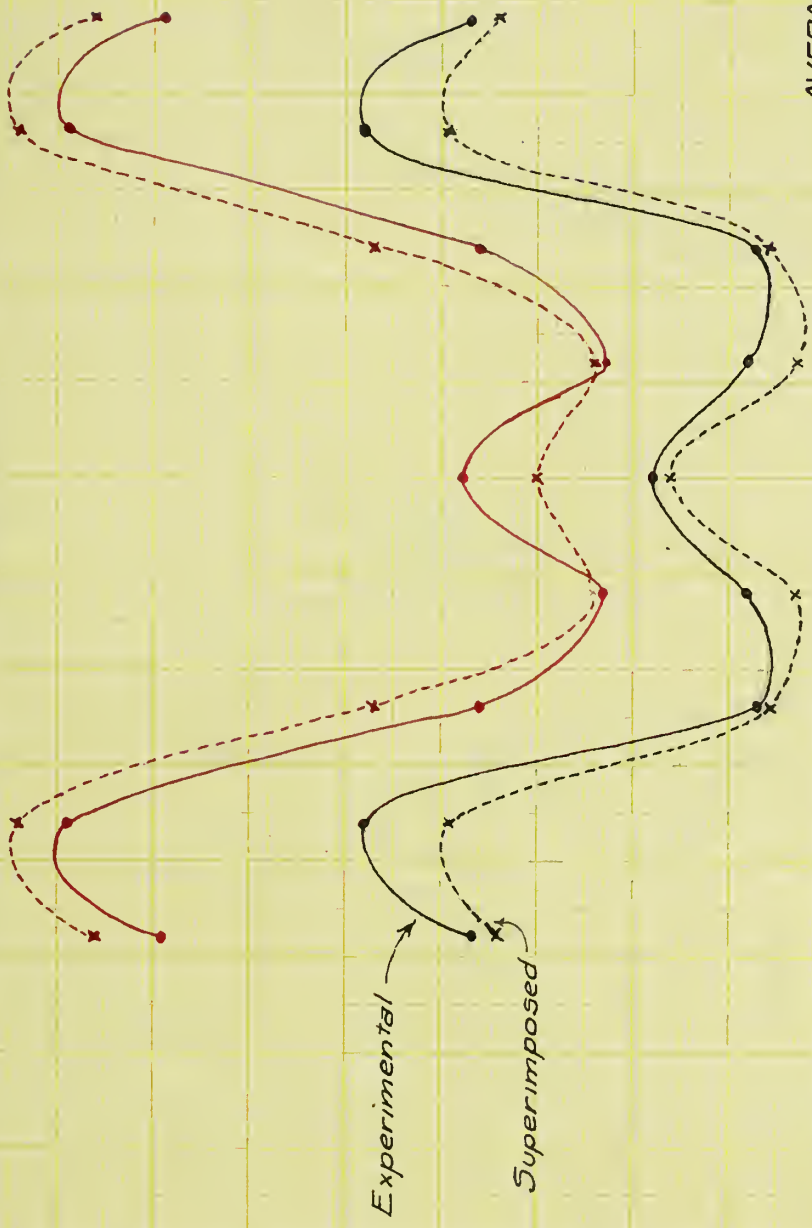
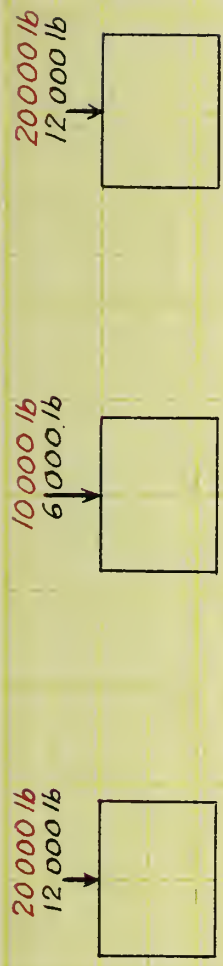
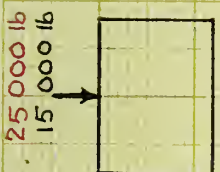
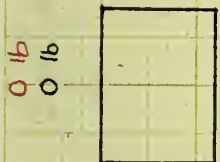
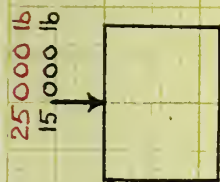


FIG. 89
AVERAGE PRESSURE CURVES
SAND BALLAST
DEPTH 18 INCHES
SERIES J



Vertical Pressure - lb. per sq. in.

16

14

12

10

8

6

4

2

Experimental

Superimposed

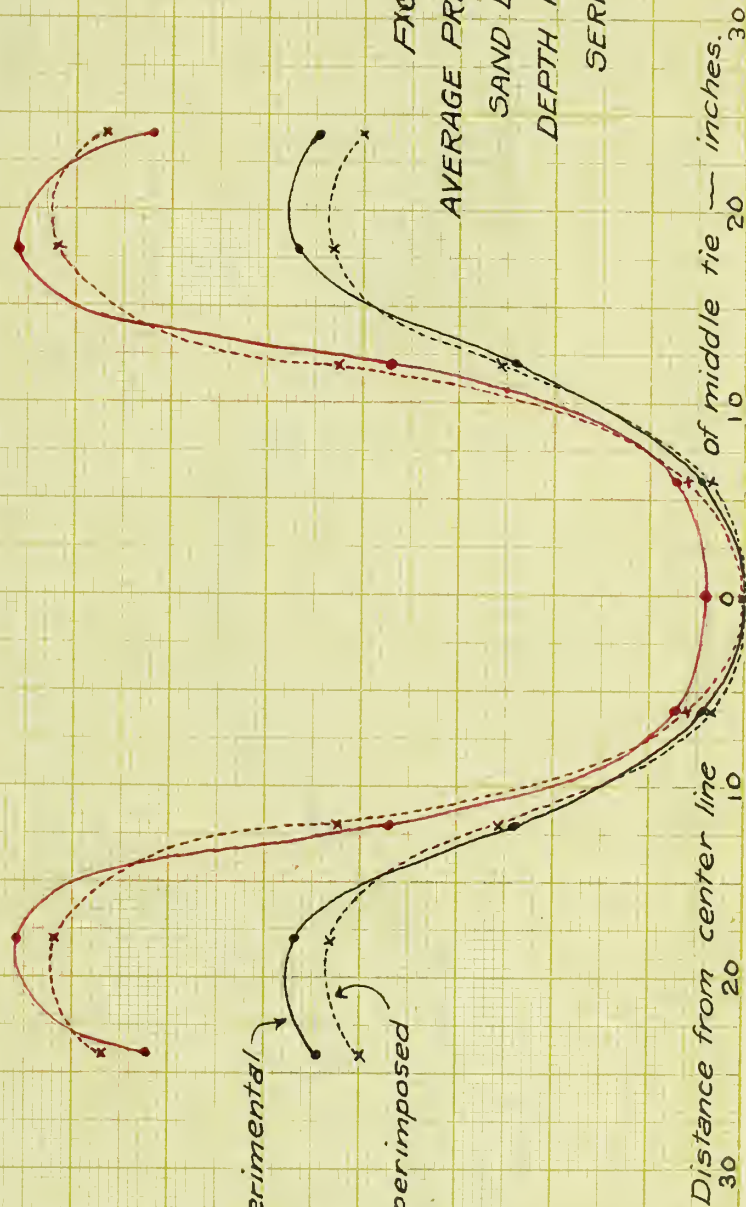


FIG. 90

AVERAGE PRESSURE CURVES

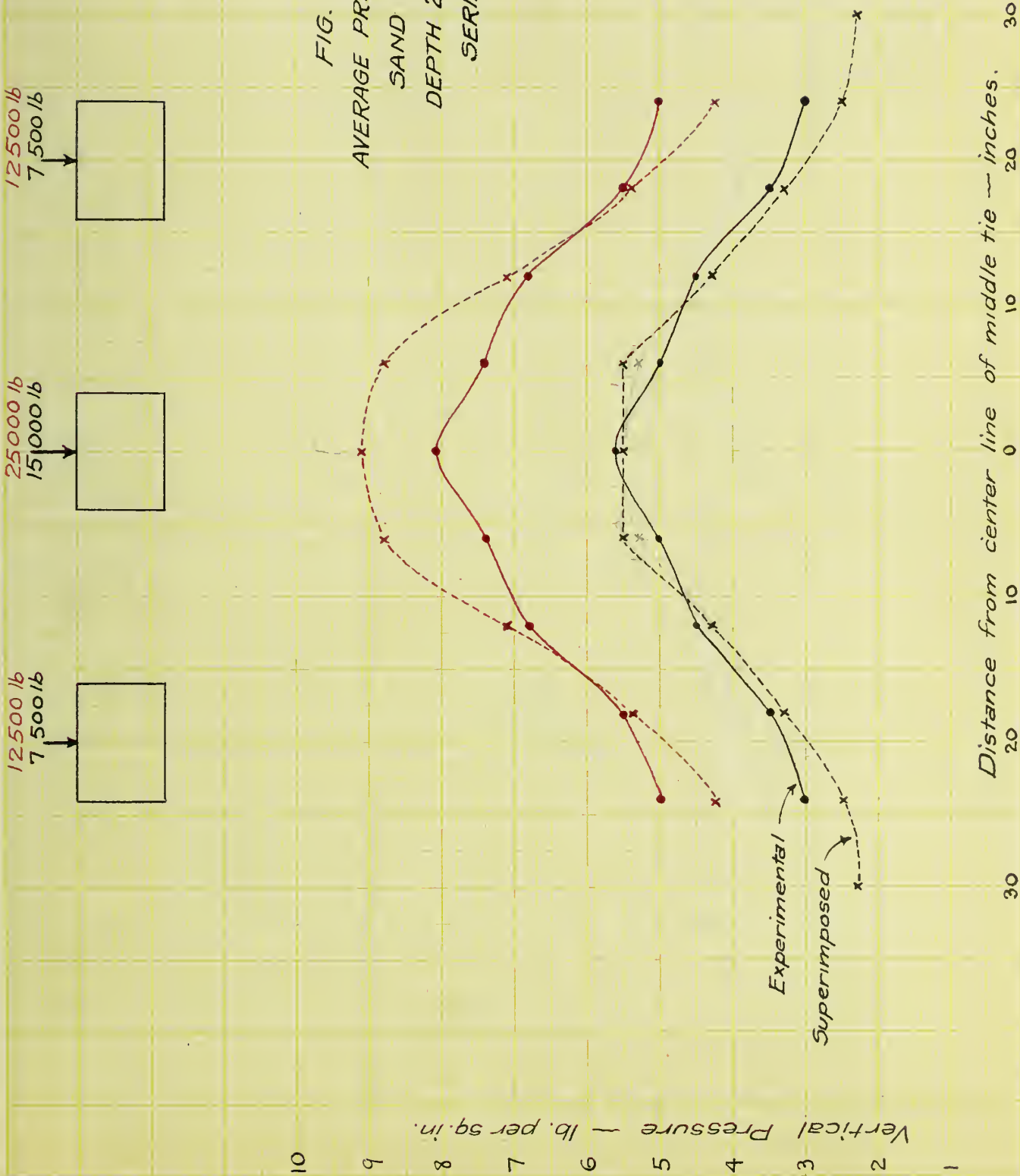
SAND BALLAST

DEPTH 18 INCHES

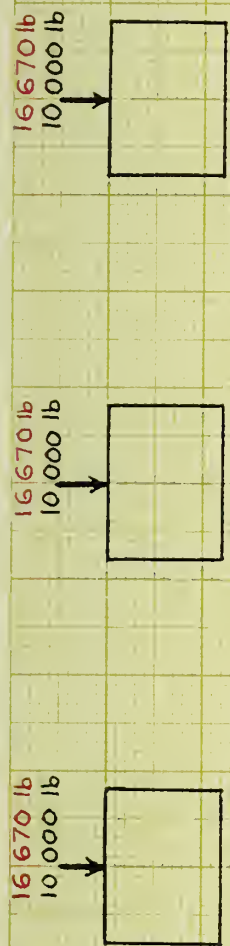
SERIES K

30 20 10 0 10 20 30

FIG. 91
AVERAGE PRESSURE CURVES
SAND BALLAST
DEPTH 25 INCHES
SERIES M







Vertical Pressure - lb. per sq. in.

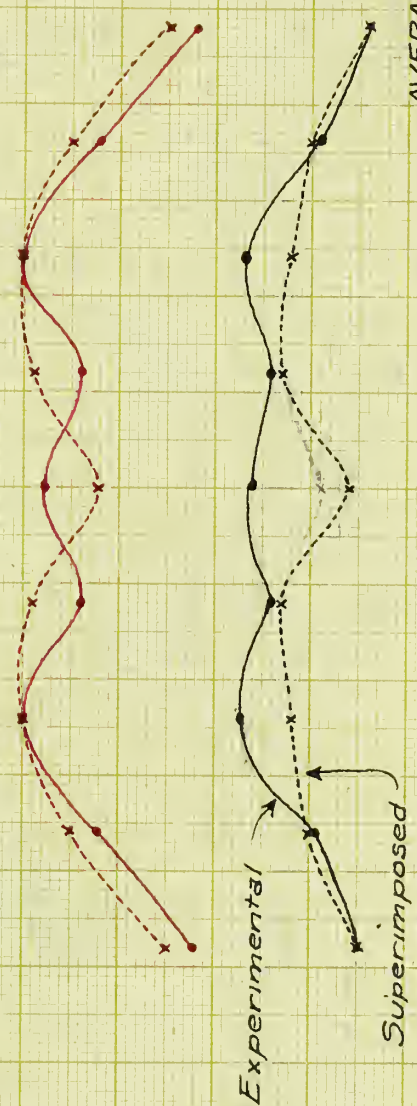
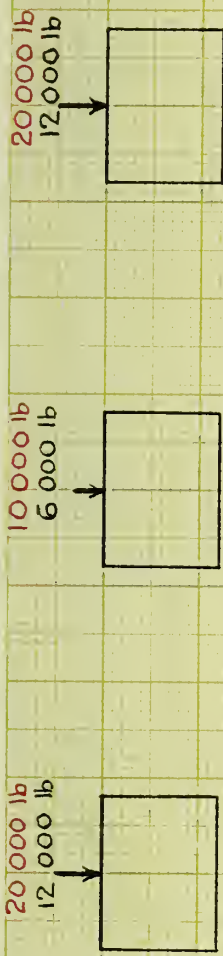
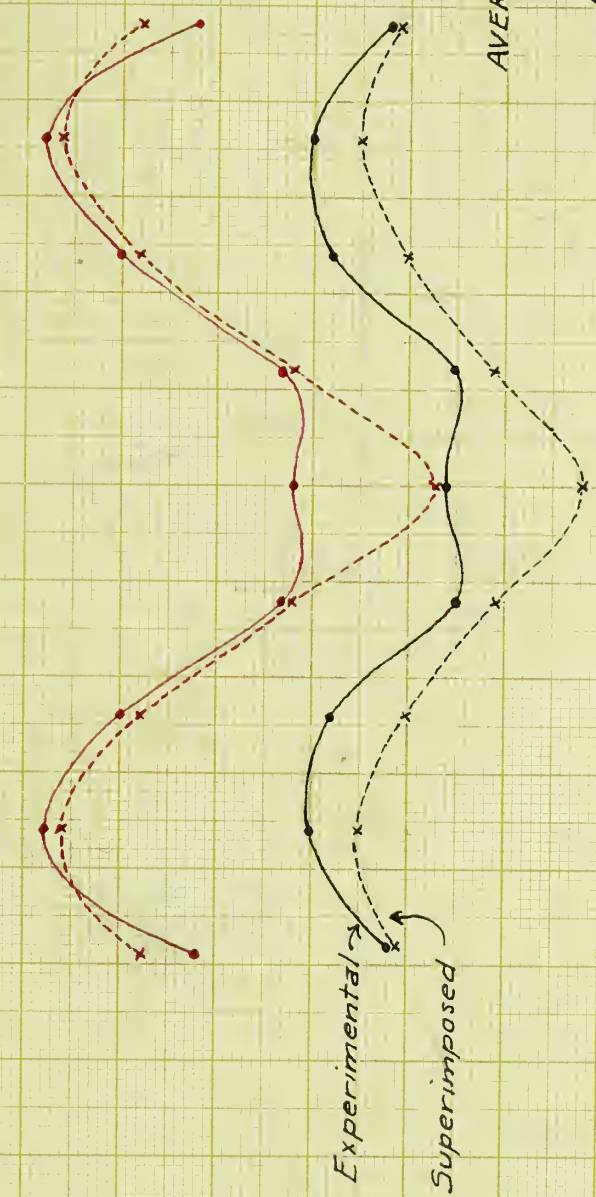


FIG. 92
AVERAGE PRESSURE CURVES
SAND BALLAST
DEPTH 25 INCHES.
SERIES N.

Distance from center line of middle tie - inches



Vertical Pressure - lb. per sq. in.



Experimental
Superimposed

FIG. 93
AVERAGE PRESSURE CURVES
SAND BALLAST
DEPTH 25 INCHES
SERIES 0

Distance from center line of middle tie - inches

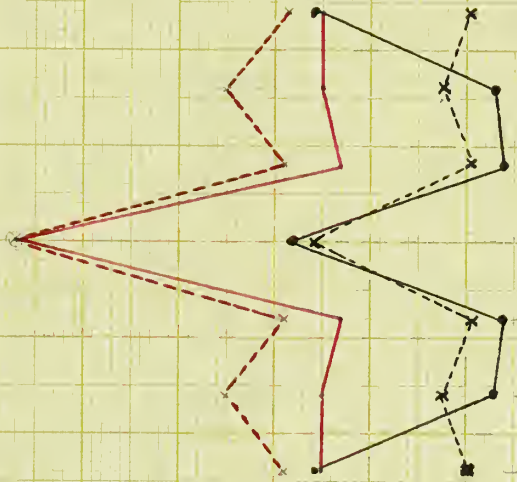
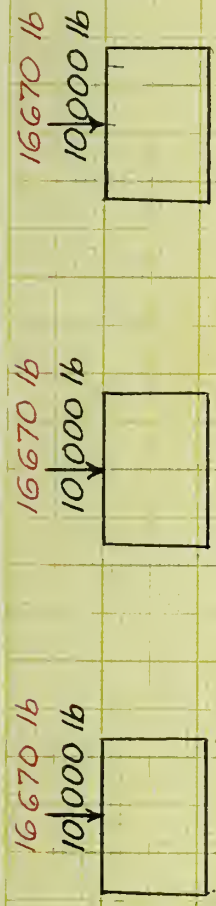


FIG. 94
AVERAGE PRESSURE CURVES
ROCK BALLAST
DEPTH 12 INCHES.

Experimental values shown by full line.
Values obtained by superimposing the
experimental results for a single tie
shown by broken line.

Dist. from center line of middle tie-inches

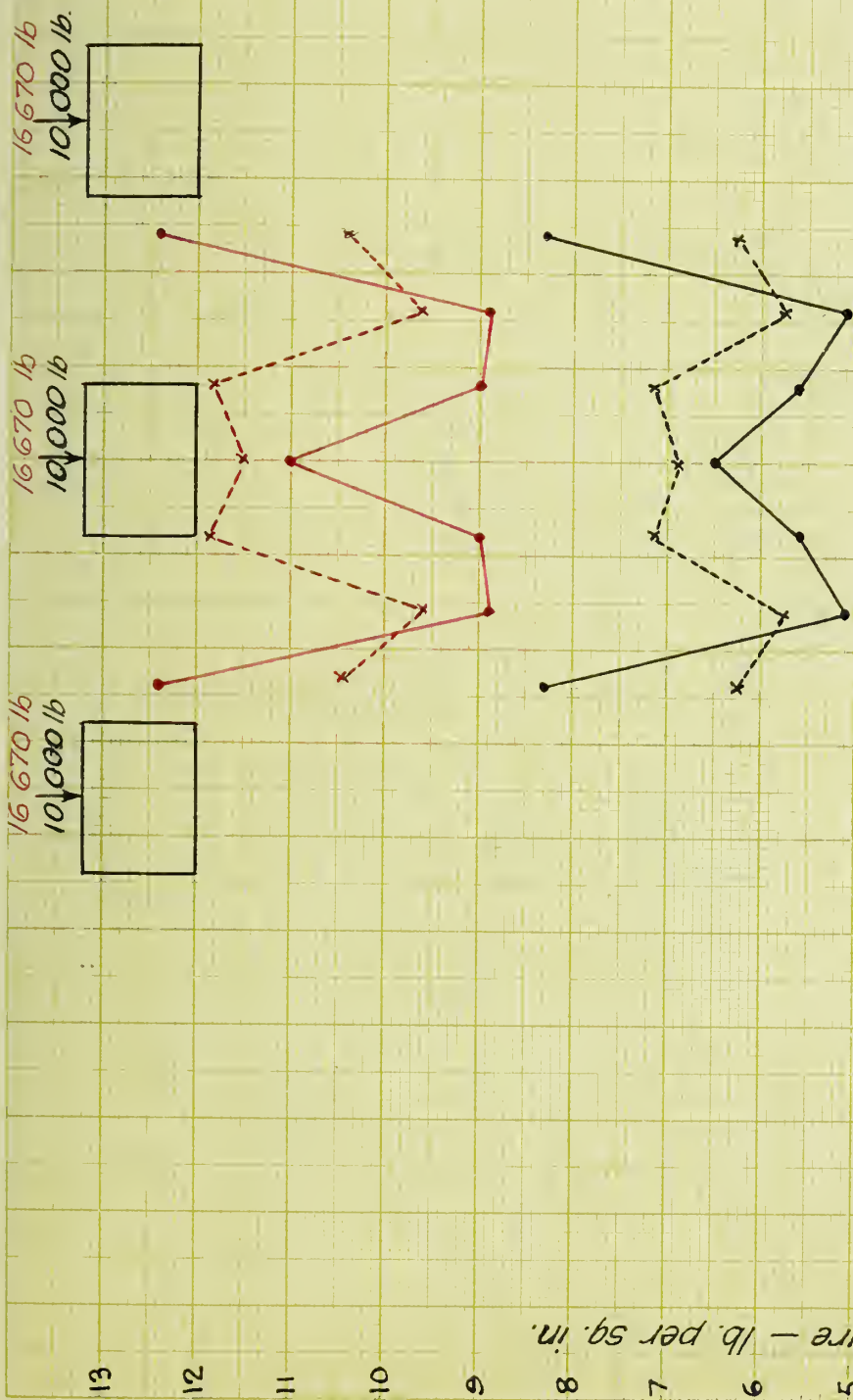


FIG. 95
AVERAGE PRESSURE CURVES
ROCK BALLAST
DEPTH 18 INCHES.

Distance from center line of middle tie-inches

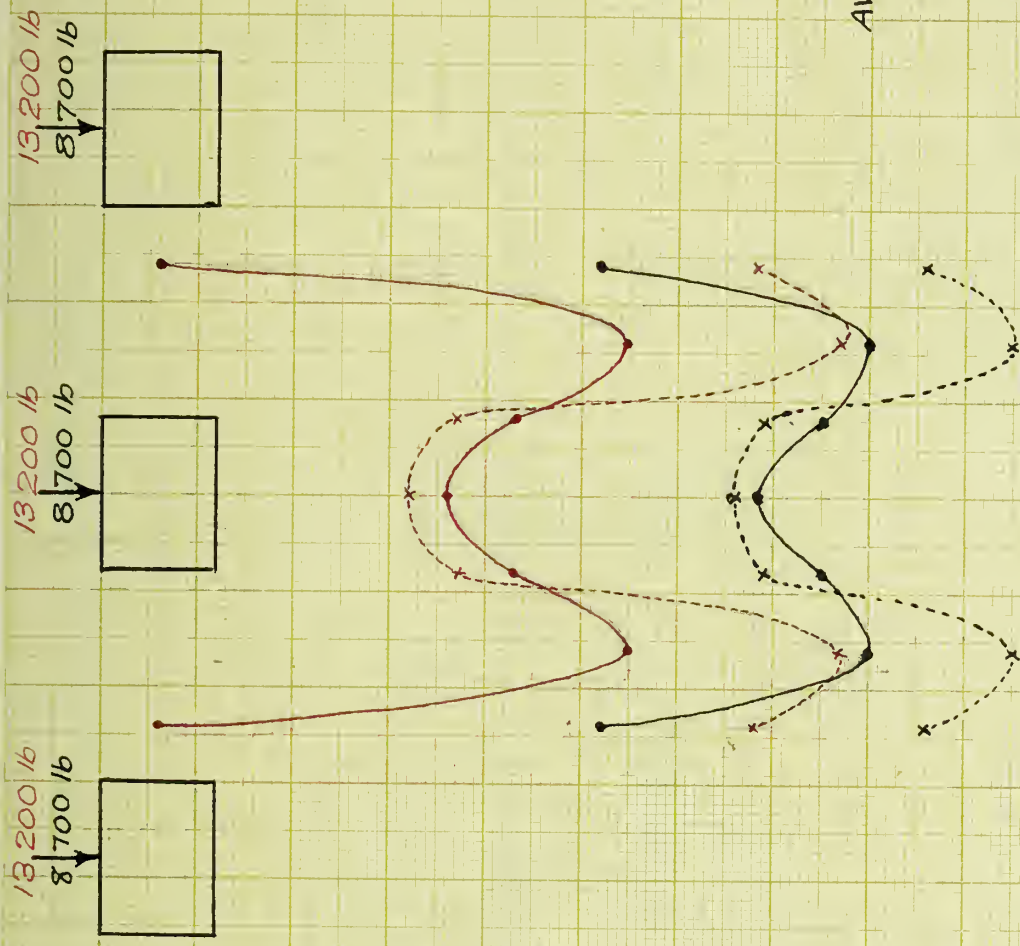


FIG. 96
 AVERAGE PRESSURE CURVES
 GRAVEL BALLAST.
 DEPTH 12 INCHES.

Distance from Center Line of Middle Tie - inches.

Vertical Pressure - Pounds per Square Inch.

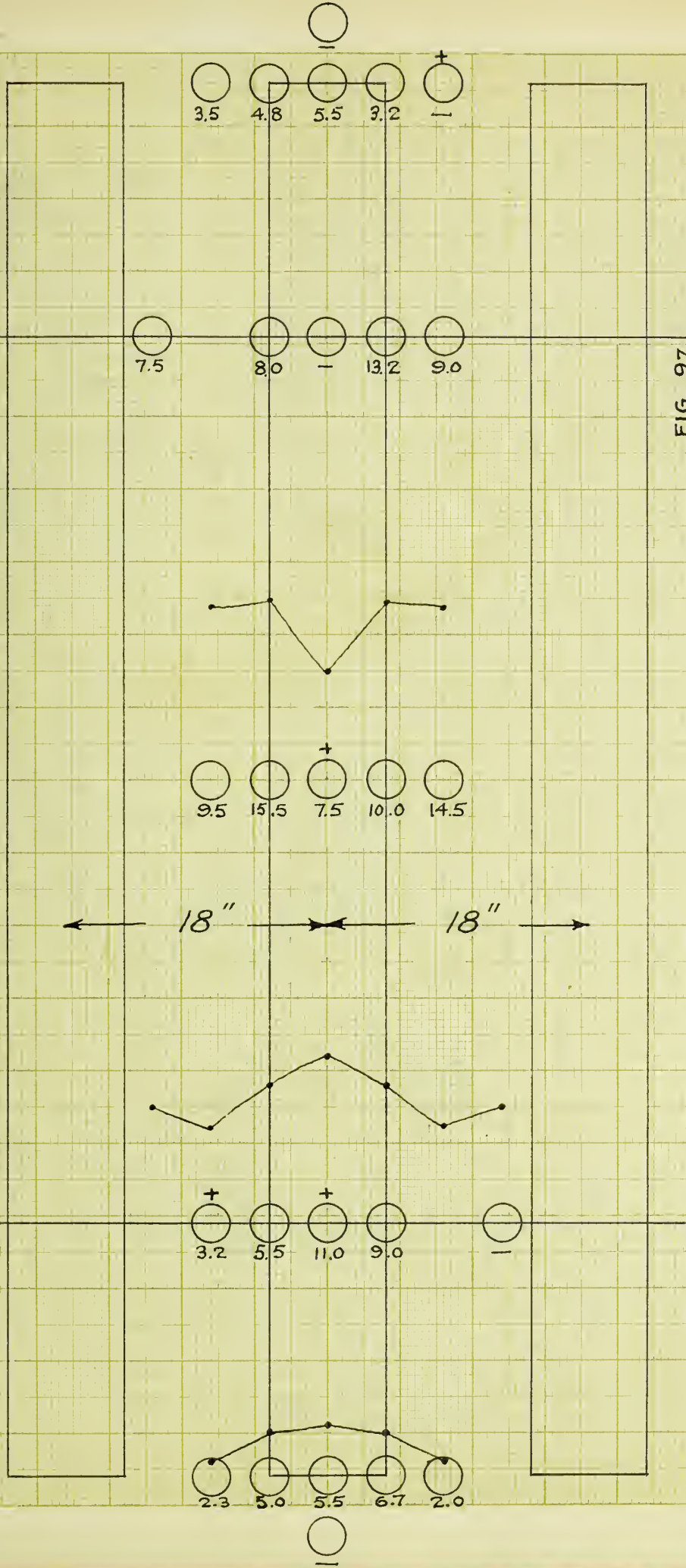


FIG. 97

FIRST 163 LOADINGS

SAND BALLAST

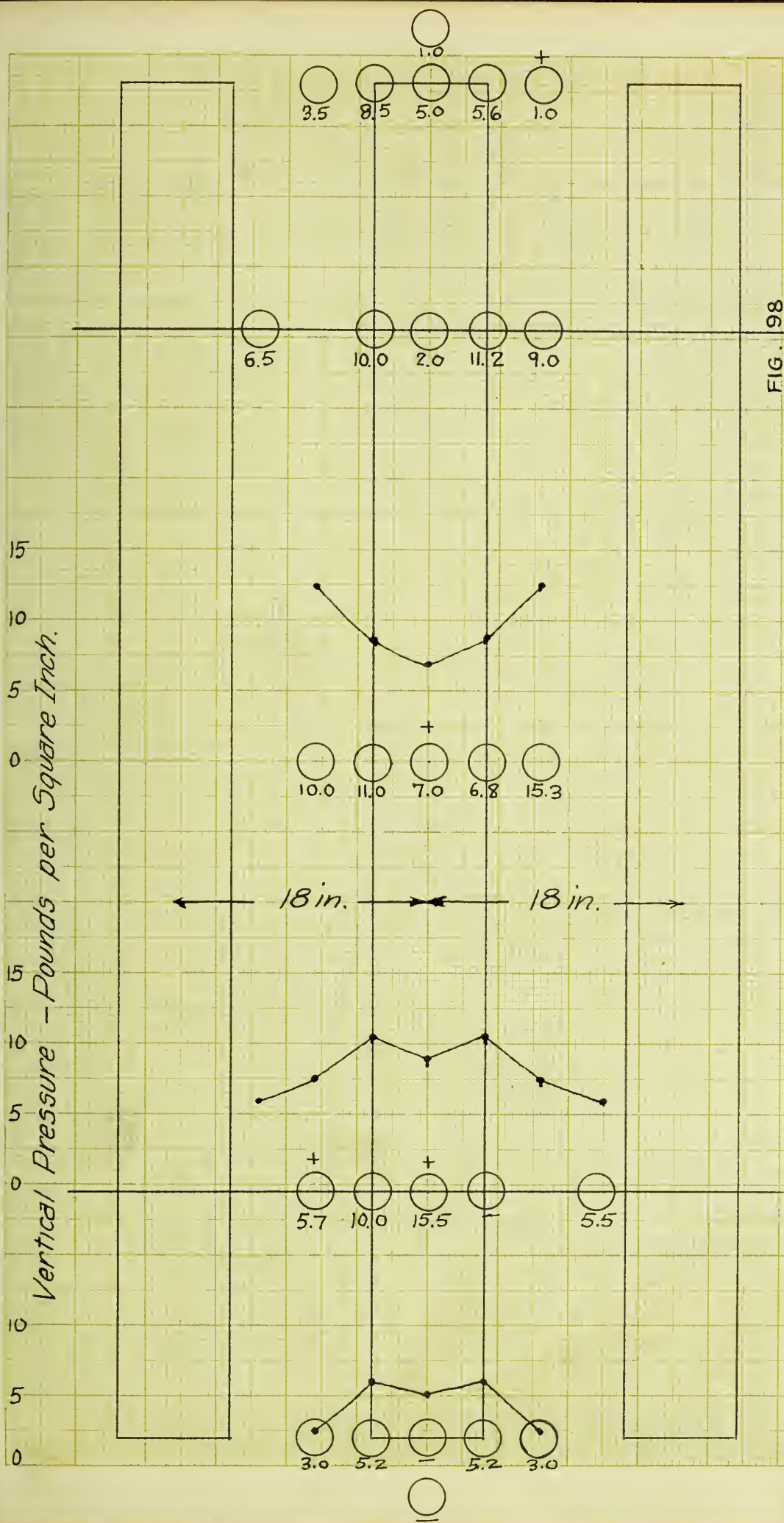
DEPTH 18 IN.

THREE TIES

25% 50% 25%

TOTAL LOAD 39500 LB.

Capsules indicated + were found in bad order when taken out.



LOADINGS 164 TO 300

SAND BALLAST

DEPTH 18 IN.

THREE TIES

25% 50% 25%

TOTAL LOAD 39500 LB.

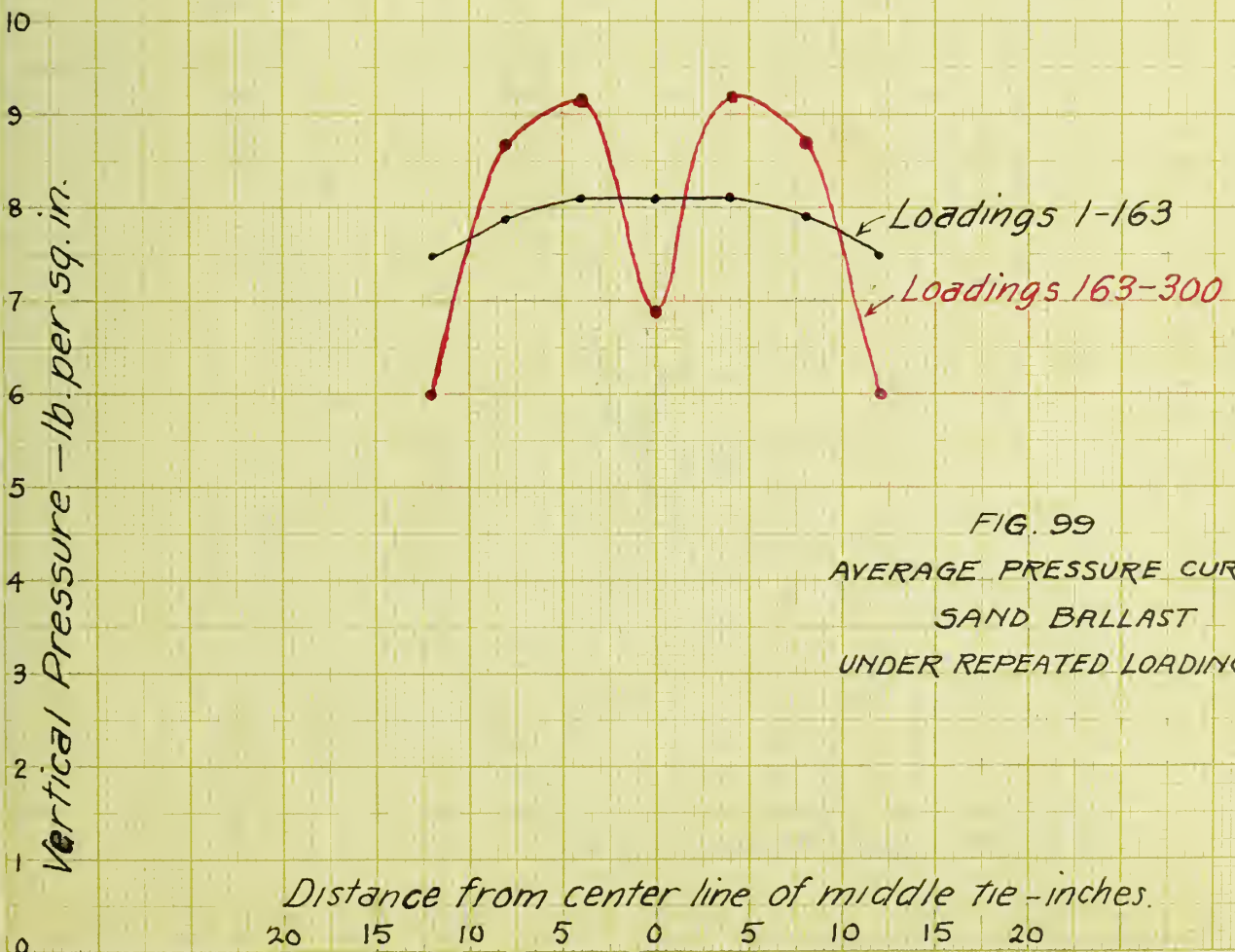
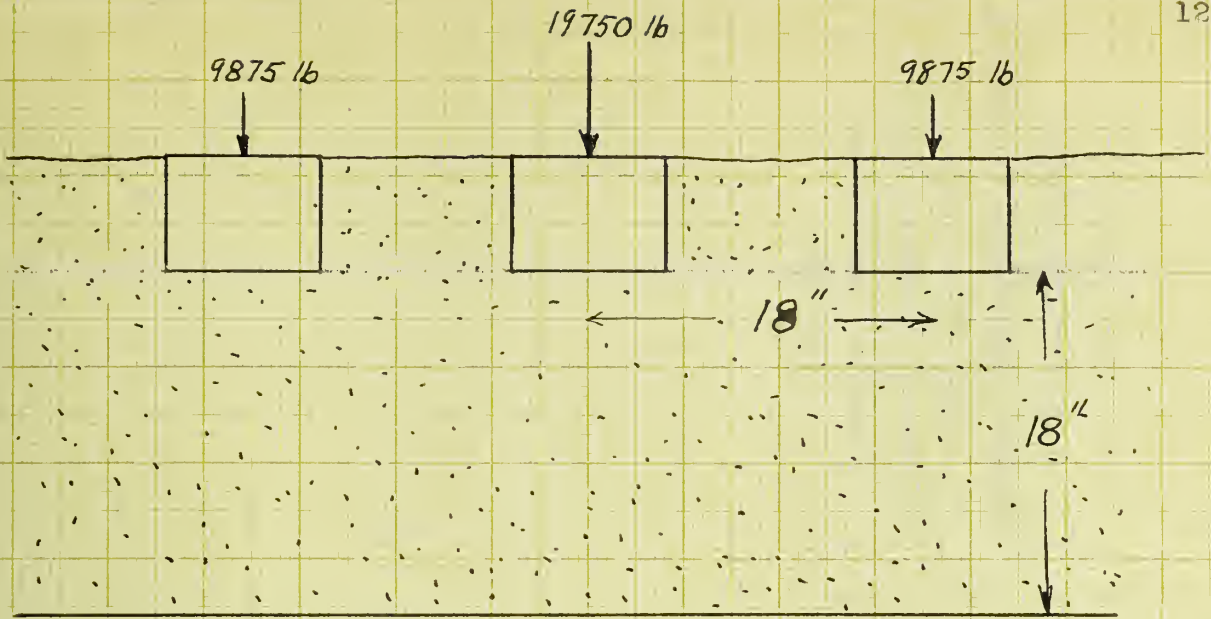


FIG. 99
AVERAGE PRESSURE CURVES
SAND BALLAST
UNDER REPEATED LOADINGS

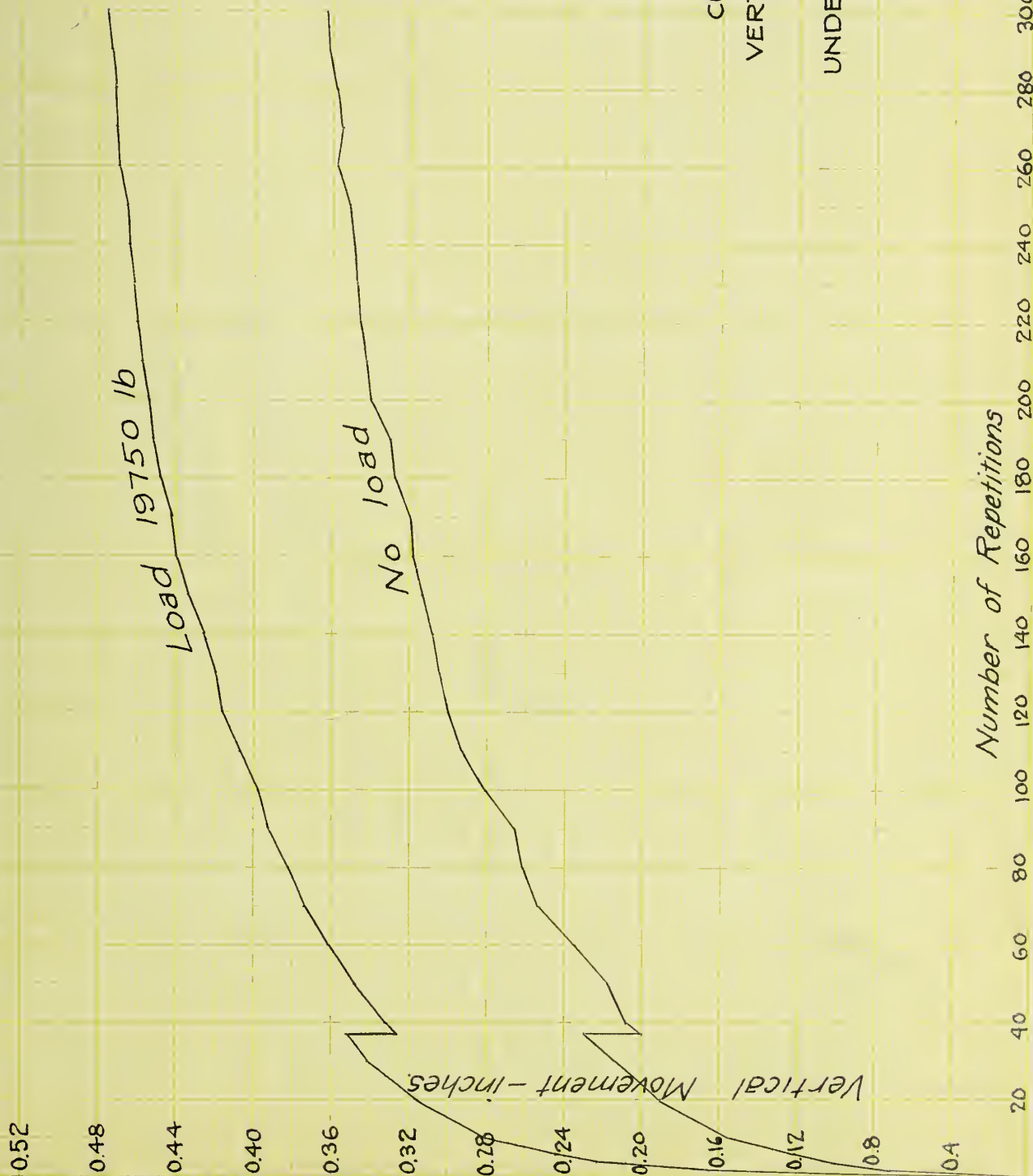


FIG. 100
CURVES SHOWING
VERTICAL MOVEMENT OF
ENDS OF TIE
UNDER REPEATED LOADINGS
SAND BALLAST
DEPTH 18 IN.

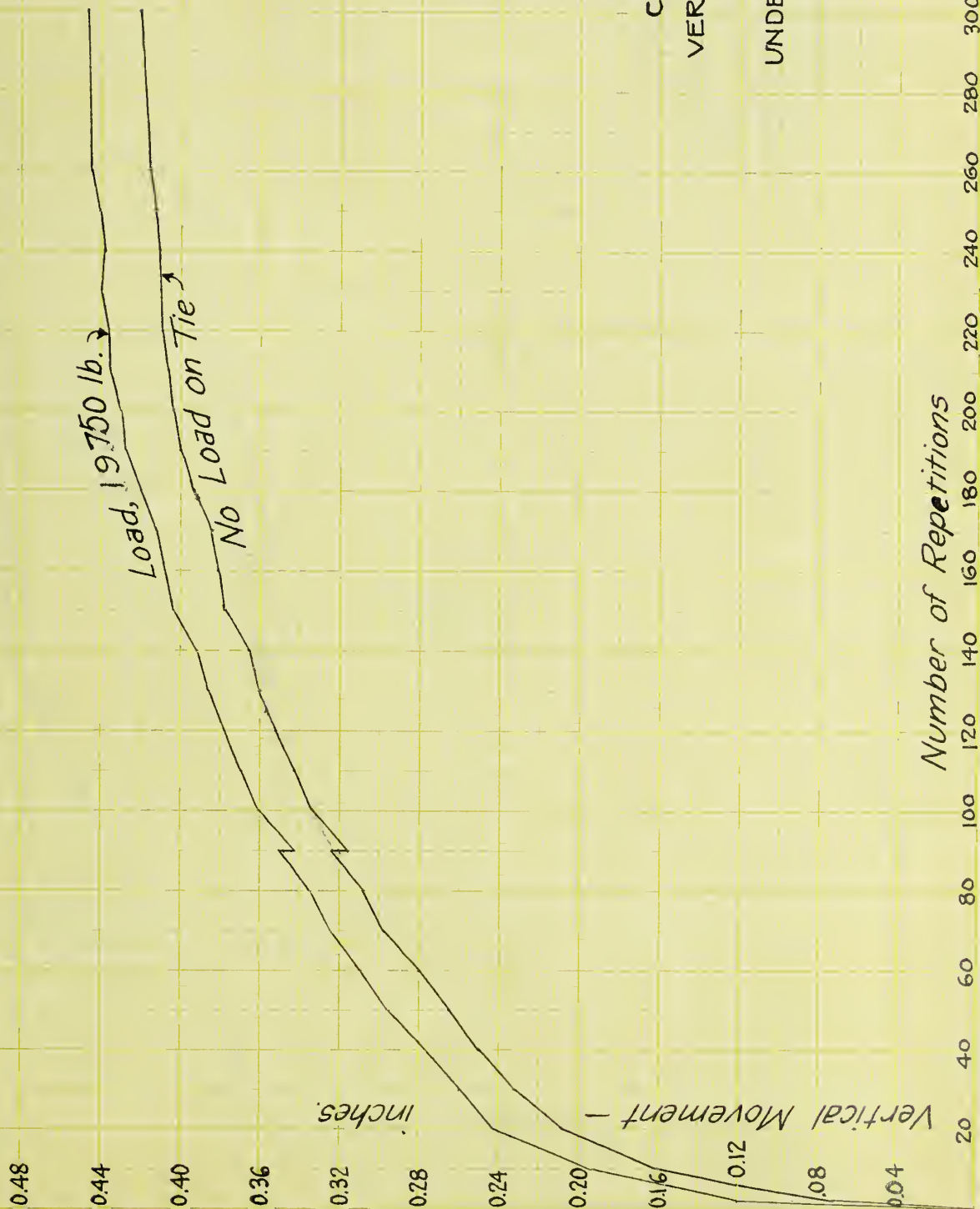


FIG. 101

CURVES SHOWING
VERTICAL MOVEMENT OF
CENTER OF TIE
UNDER REPEATED LOADINGS
SAND BALLAST
DEPTH 18 IN.

Number of Repetitions

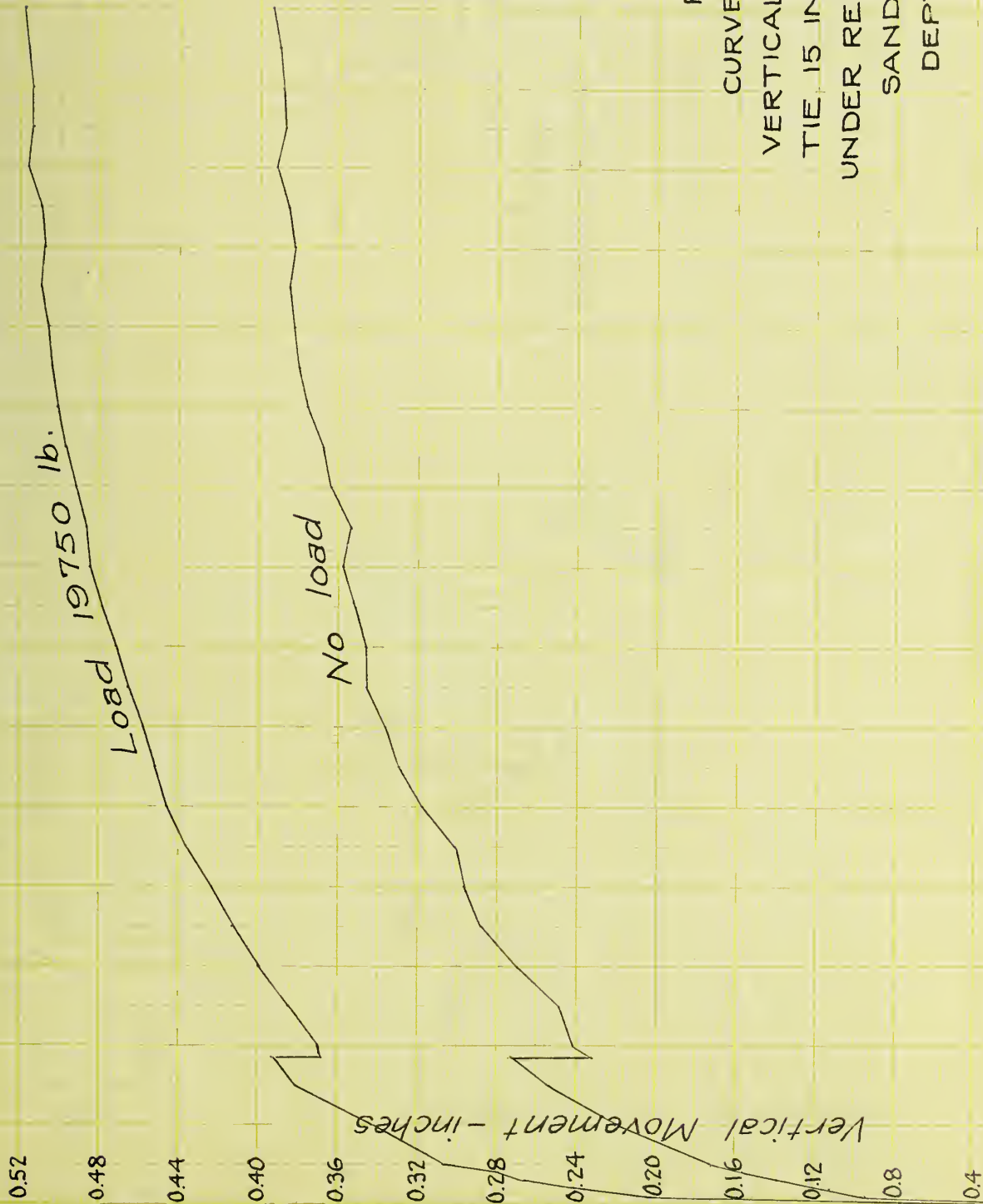


FIG 102
 CURVES SHOWING
 VERTICAL MOVEMENT OF
 TIE 15 INCHES FROM ENDS
 UNDER REPEATED LOADINGS
 SAND BALLAST
 DEPTH 18 IN.

Number of Repetitions

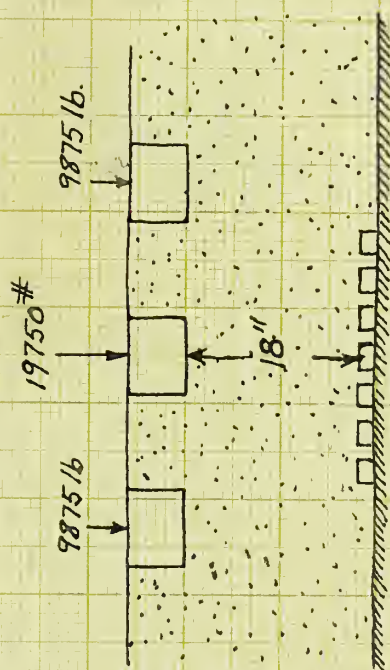
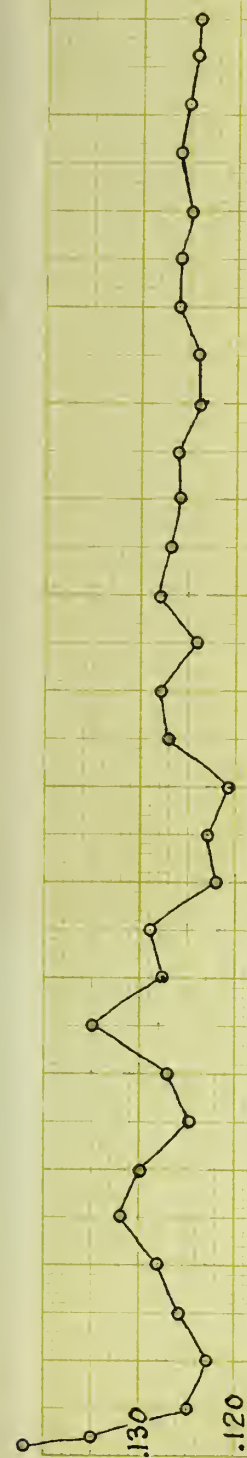


Fig. 103

Elastic

Depression of Tie

15 Inches from End of Tie (middle)

Under Action of Repeated Load.

Total Load 39500 lb.

Three Ties

25%, 50%, 25% Loading

Depth 20 in.

Number of Applications of Load

Depression of Tie - inches

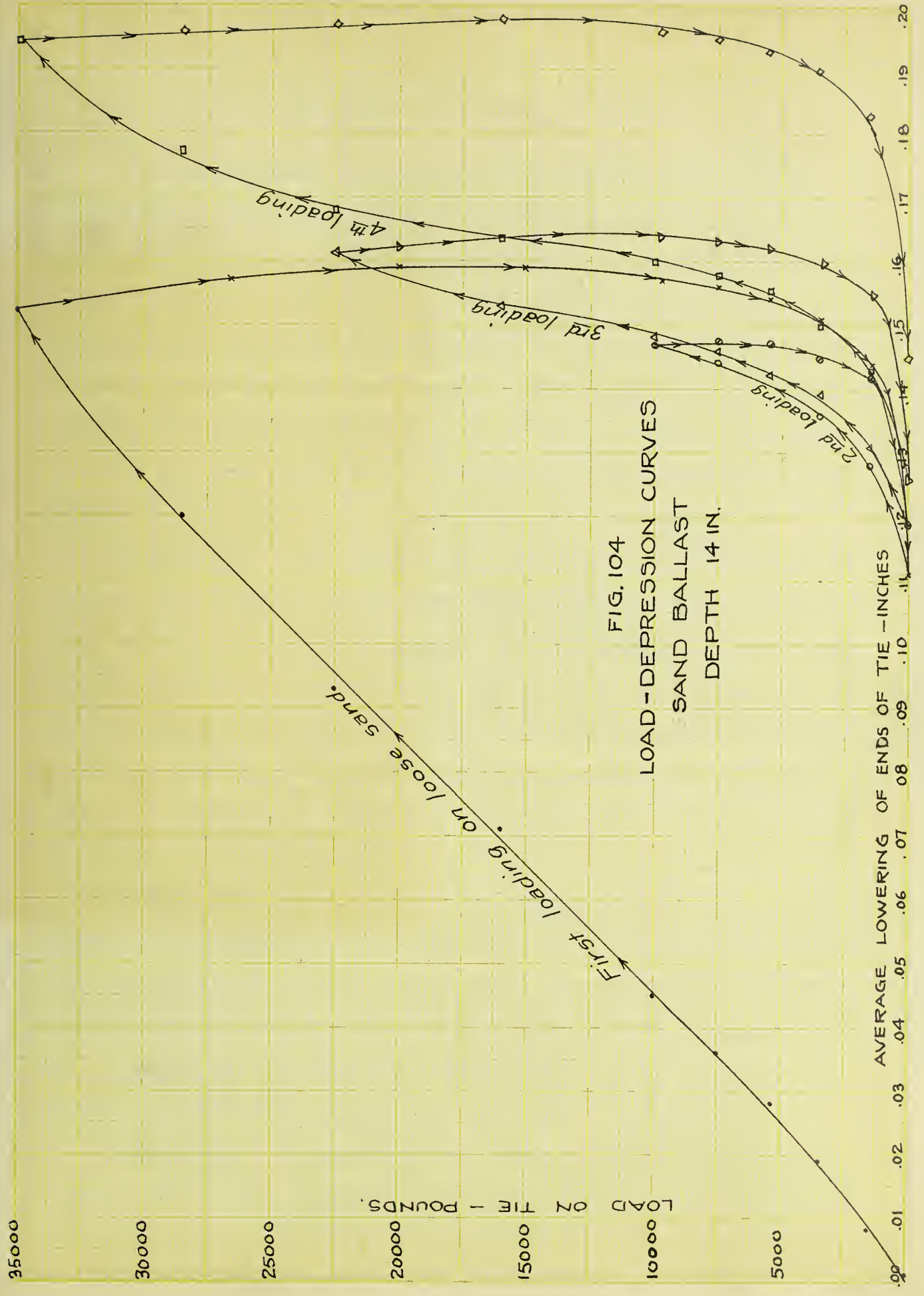


FIG. 104
LOAD-DEPRESSION CURVES
SAND BALLAST
DEPTH 14 IN.

VI. EXPERIMENTS WITH CIRCULAR PLATES.

The experiments to determine the distribution of the vertical pressure at different distances below circular plates of various diameters will be listed below in the order in which they were made. The order of the experiments is of some importance in interpreting the results, because of the compacting action of the plates when loaded. This fact was not foreseen, and in the earlier experiments no attempt was made to loosen up the sand when the experiments on one size of plate had been completed. In the later experiments this was done.

Series 1c. Sand ballast 38 inches deep, 21 inch circular plate. The maximum load was determined by the "yield point" of the ballast. The upward pressure of the concrete against the ballast was computed from the readings of the capsules, and it was found to be only 28.8% of the pressure applied to the circular plate, when certain negative readings are included. When the negative readings are excluded 41% of the downward pressure is accounted for.

Series 1c'. Sand ballast 38 inches deep, 21 inch circular plate. A repetition of the experiments of the preceding series. The compacting action of the previous loads allowed a somewhat larger load to be carried. 56.3% of the load was accounted for.

Series 1a. Sand ballast 38 inches deep, 36 inch circular plate. 56.5% of the load accounted for.

Series 2a. Sand ballast 30 inches deep, 36 inch circular plate. The upward pressure as determined from the readings of the capsules was 85.6% of the applied load.

Series 2b. Sand ballast 30 inches deep, 30 inch circular plate. The upward pressure calculated from the readings of the capsules was 84.9% of the applied load.

Series 2c. Sand ballast 30 inches deep, 21 inch circular plate. The total upward pressure determined from the readings of the capsules was 93.2% of the applied load.

Series 2d. Sand ballast, 30 inches deep, 13.5 inch circular plate. The total upward pressure determined by the capsules is 76.5% of the applied load.

Series 3a. Sand ballast 24 inches deep, 36 inch circular plate. The total upward pressure determined from the readings of the capsules was 102.2% of the applied load.

Series 3a'. Sand ballast 24 inches deep, 36 inch circular plate. This series was a repetition of the preceding series, after loosening the sand beneath the plate. Loosening up the sand had a considerable effect upon the distribution of the pressure. In the experiments which follow the sand was always loosened before putting on a plate of different diameter. The upward pressure determined from the readings of the pressure capsules was 97.5% of the applied load.

Series 3b. Sand ballast 24 inches deep, 30 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 120% of the applied load.

Series 3c. Sand ballast 24 inches deep, 21 inch circular plate. The total upward pressure, determined by the pressure capsule, was 123.6% of the applied load.

Series 3d. Sand ballast 24 inches deep, 13.5 inch circular plate. The total upward pressure, determined by the pressure

capsule readings, was 115.6% of the applied load.

Series 4a. Sand ballast 18 inches deep, 36 inch circular plate. The total upward pressure, determined by the pressure capsules, was 116.1% of the applied load.

Series 4b. Sand ballast 18 inches deep, 30 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 130% of the applied load.

Series 4c. Sand ballast 18 inches deep, 21 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 136% of the applied load.

Series 4d. Sand ballast 18 inches deep, 13.5 inch plate. The total upward pressure, as determined by means of the pressure capsule, was 150% of the applied load.

Series 5a. Sand ballast 12 inches deep, 36 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 117.5% of the applied load.

Series 5b. Sand ballast 12 inches deep, 30 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 132% of the applied load.

Series 5c. Sand ballast 12 inches deep, 21 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 143% of the applied load.

Series 5d. Sand ballast 12 inches deep, 13.5 inch circular plate. The total upward pressure, as determined by the pressure capsules, was 124.6% of the applied load.

Series 5d'. Same as Series 5d, except that the sand ballast was wet. The total upward pressure, as determined by the pressure capsules, was 112% of the applied load.

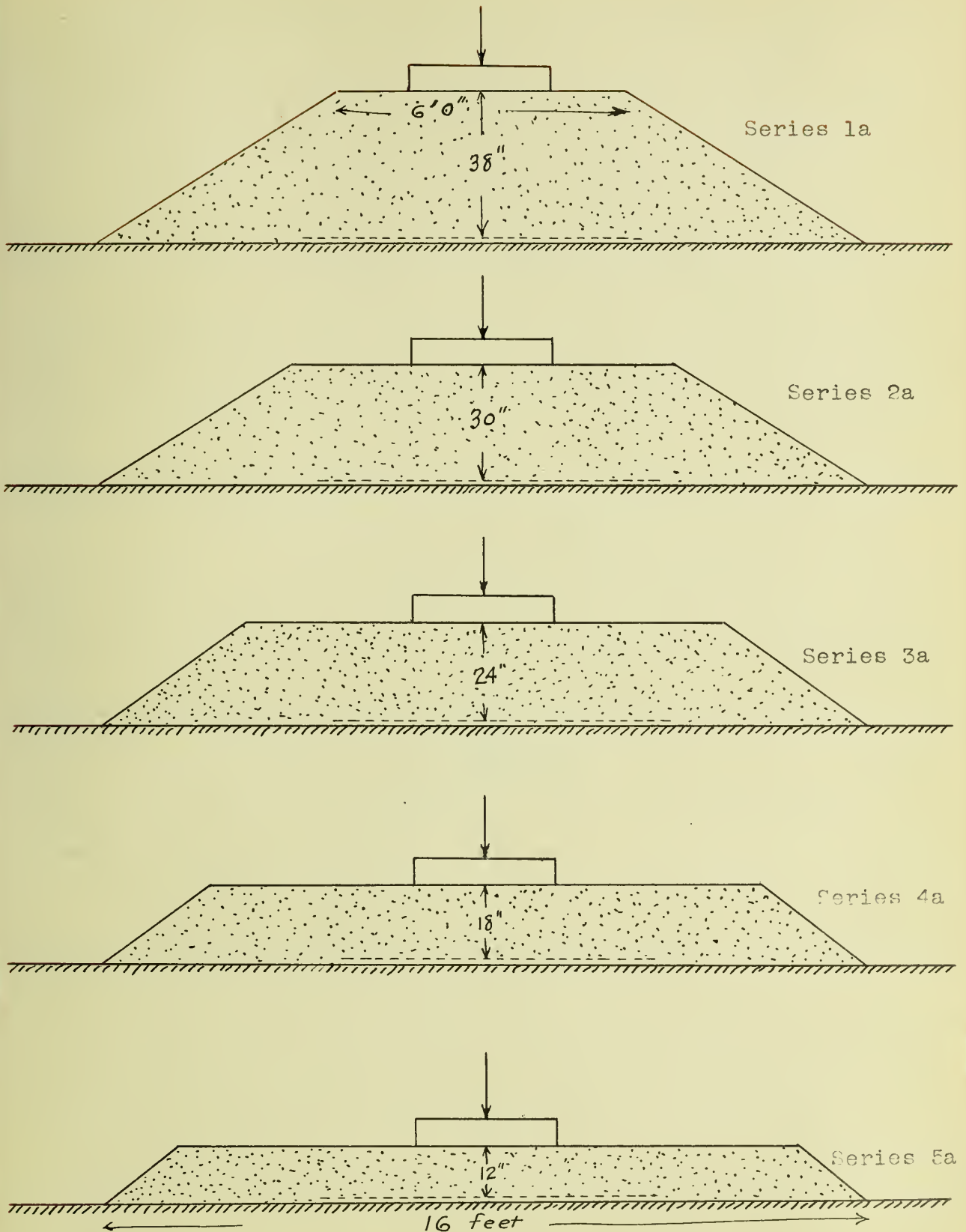


FIG. 105

The figures show the general dimensions of the sand pile used in the experiments with circular plates.

Results of Experiments with Circular Plates. A comparison of the experiments with circular plates with the earlier experiments is made on the logarithmic diagram in Fig. 107. It will be seen that the agreement is close for the 38 inch depth, but that it is not as good for the lesser depths of ballast. The difference may perhaps be explained by the difference in the procedure in making the experiments. In the earlier experiments much higher intensities of pressure were used. The plate was started at a depth several inches greater than the depth for which readings were taken and the plate was forced down to the desired depth. As a result the sand beneath the plate flowed laterally and was compacted near the center of the plate. If this procedure had been followed in the later experiments, it is probable that the results would have been in better agreement. It would of course have required enormous pressures to force the larger plates down in this manner when the depth of the ballast was 12 inches or 18 inches, and it would not be possible to use such pressures without breaking many of the capsules.

In Fig. 129 to 133 curves have been plotted for the comparison of vertical pressure at different depths of ballast with respect to the distance from the edge of the plates. It will be noted that the intensity of pressure directly below the edge of the plates does not differ much for the different diameters of plate.

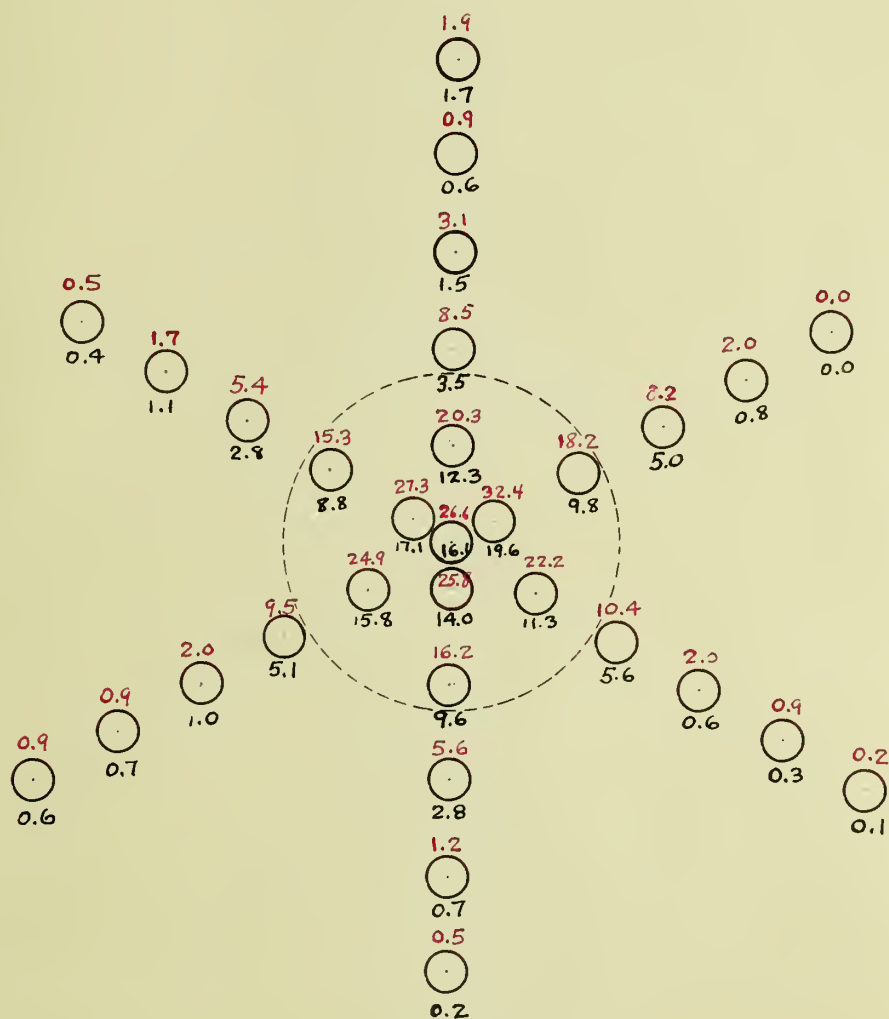
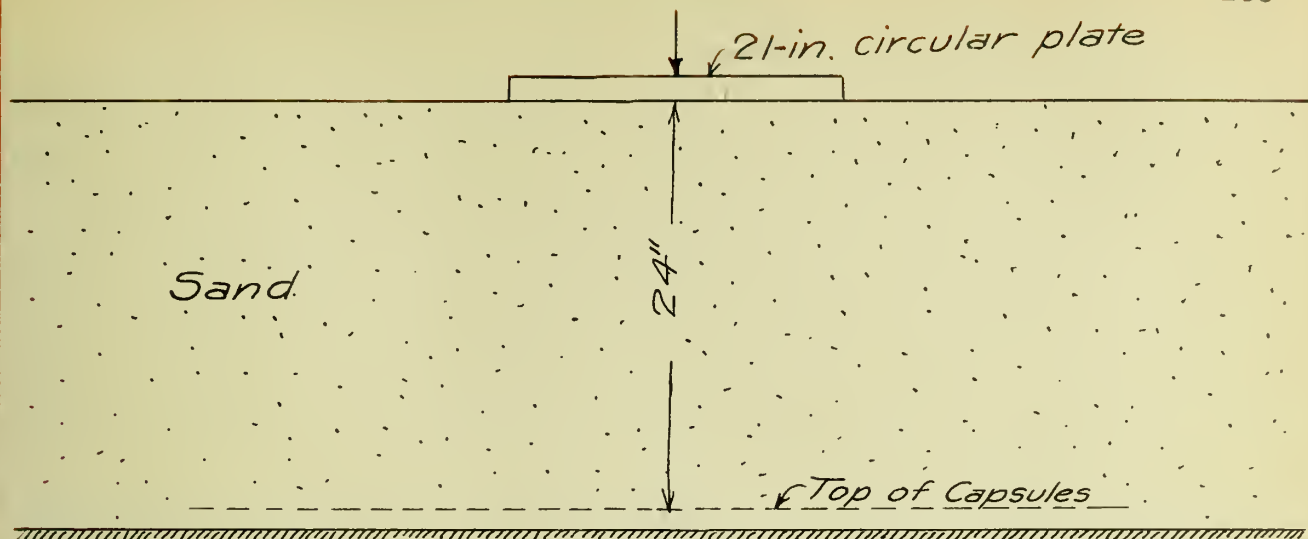


FIG. 106

Observed vertical unit-pressures in sand 24 in. below a 21-in. circular plate. Figures in black are for a load of 6700 lb., in red 13600 lb.



1880

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 Government of the
 State of New York
 in the year 1880
 by the State of New York
 in the year 1880

1880

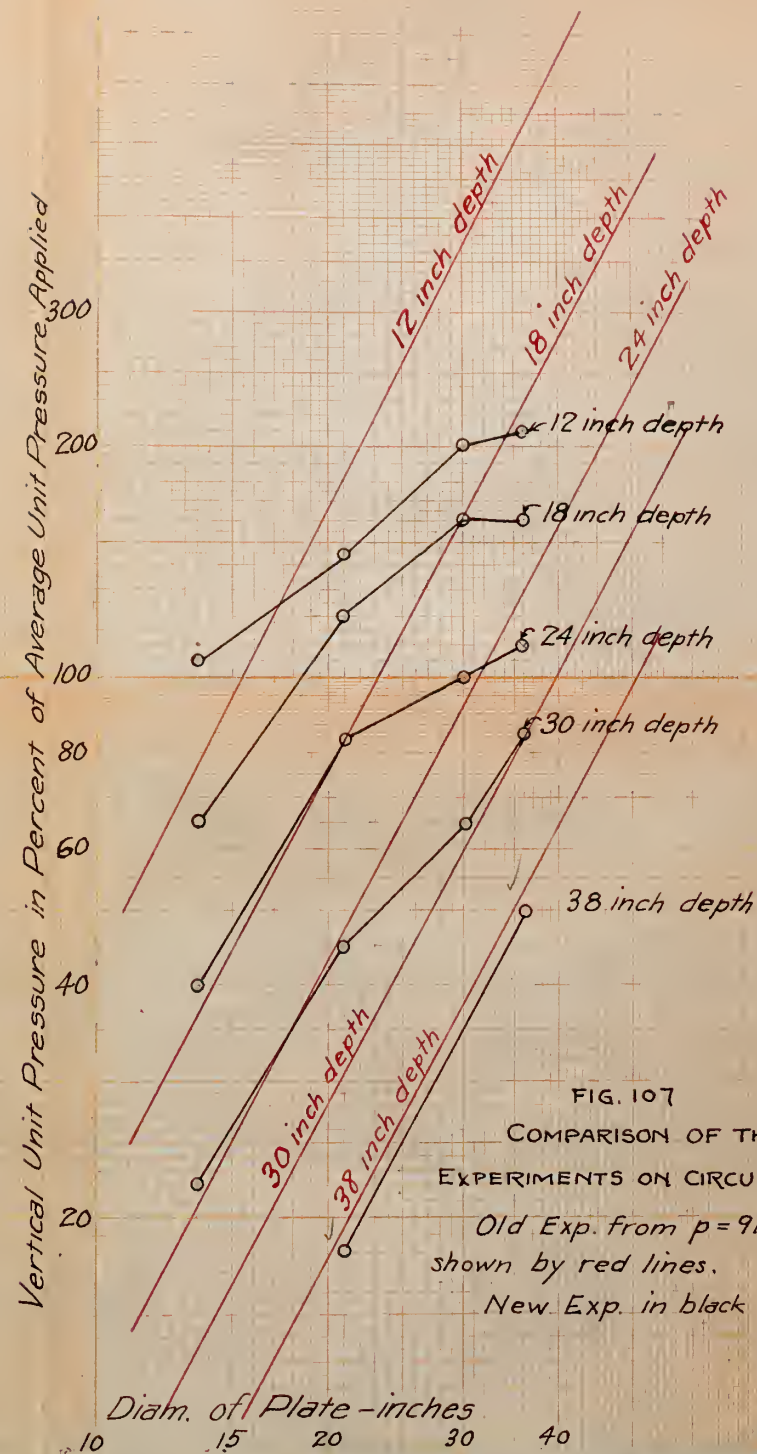
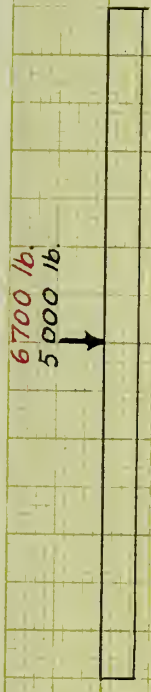


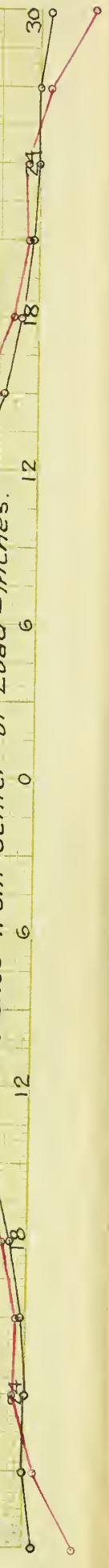
FIG. 107
COMPARISON OF THE
EXPERIMENTS ON CIRCULAR PL.
Old Exp. from $p = 91 \frac{d^{1.86}}{h^{1.95}}$
shown by red lines.
New Exp. in black

FIG. 108
SERIES 1C
SAND BALLAST 38 INCHES DEEP
21 INCH CIRCULAR PLATE



Vertical Unit-Pressure in Percent of Applied Average Unit Pressure

Distance from Center - inches.



Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

7500 lb
5000 lb



FIG. 109
SERIES 1c'
SAND BALLAST 38 INCHES DEEP
21 INCH CIRCULAR PLATE

Distance from Center of Load - inches.

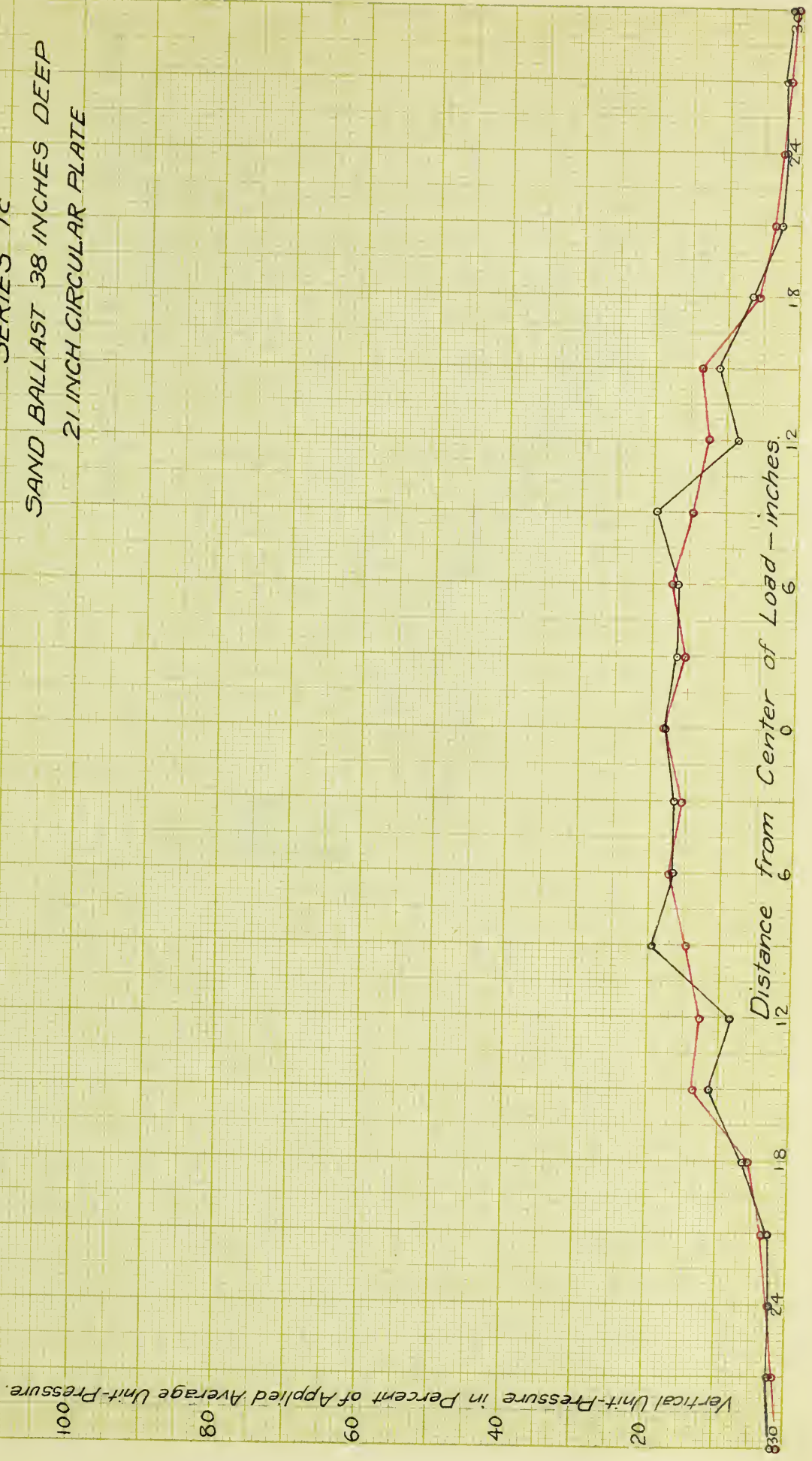


FIG. 110
 SERIES 1a
 SAND BALLAST 38 INCHES DEEP
 36 INCH CIRCULAR PLATE

Vertical Unit-Pressure in Percent of Applied Average Unit Pressure

Distance from Center of Load - inches.

100
80
60
40
20
30

30

24

18

12

6

0

6

12

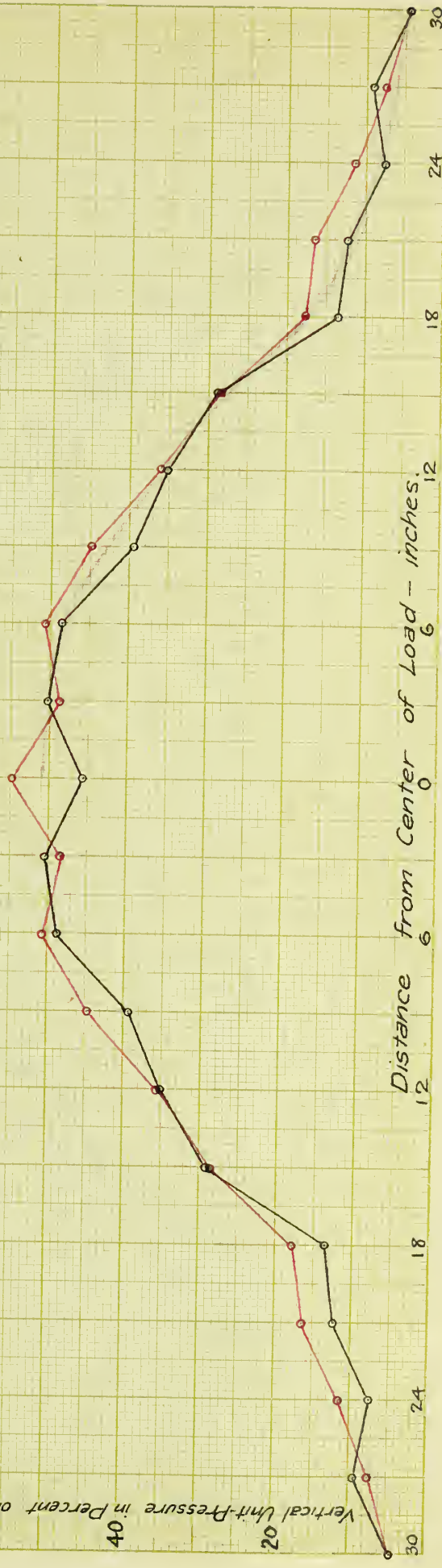
18

24

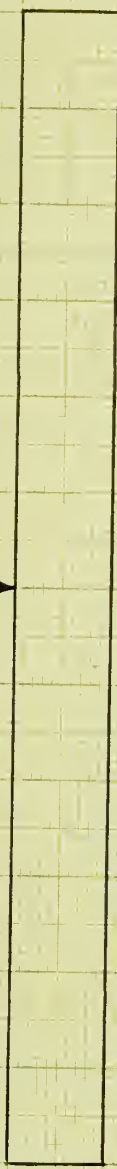
30

142

13 650 16
 6 700 16



21 800 lb.
11 900 lb.

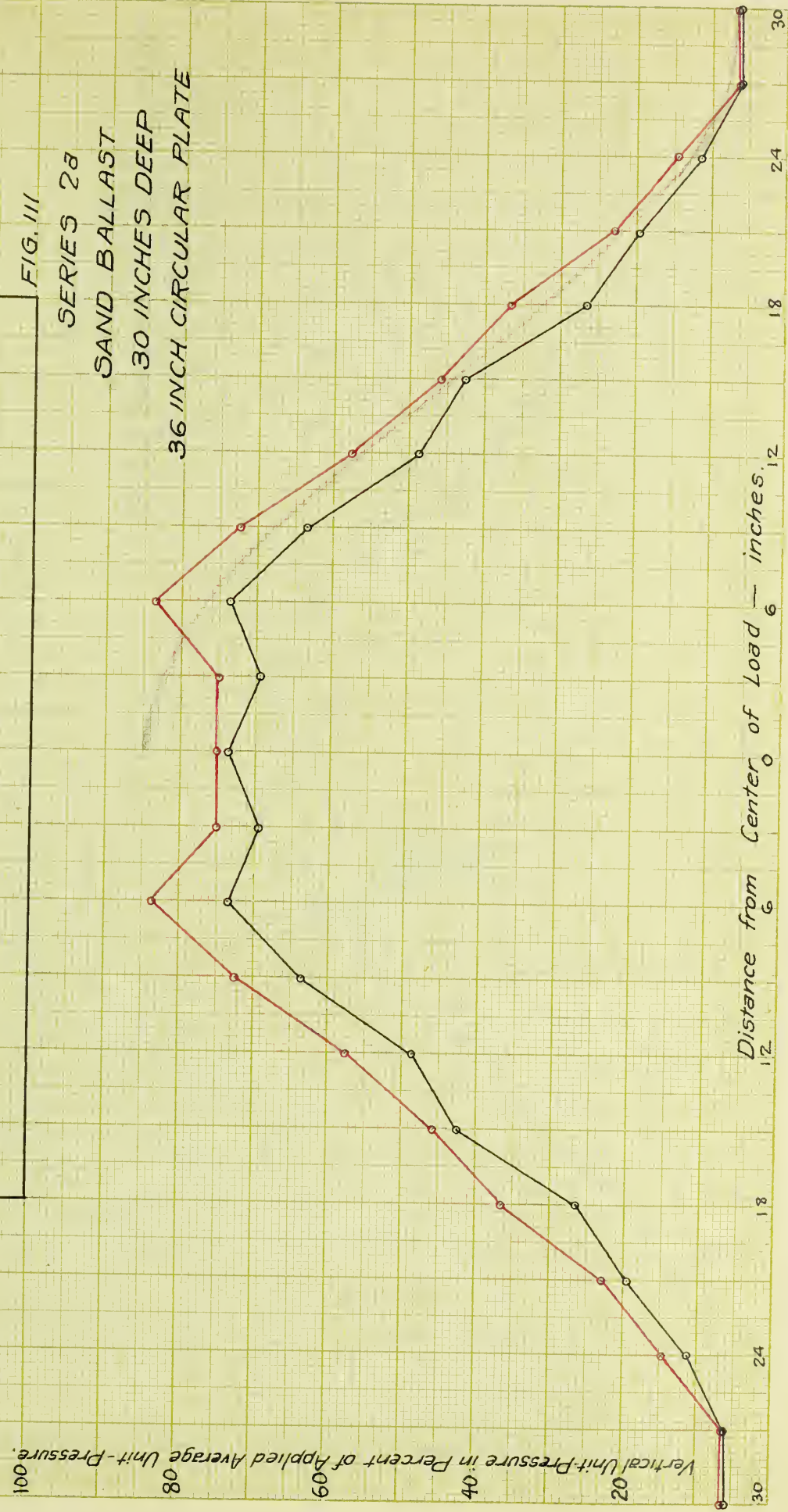


Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

FIG. III

SERIES 2a
SAND BALLAST
30 INCHES DEEP
36 INCH CIRCULAR PLATE

Distance from Center of Load — inches.



Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

15 500 lb
10 100 lb

FIG 112
SERIES 2b

SAND BALLAS 30 INCHES DEEP
30 INCH CIRCULAR PLATE

Distance from Center of Load-inches.

24

18

12

6

0

6

12

18

24

30

36

42

48

54

60

66

72

78

84

90

96

102

108

114

120

126

132

138

144

Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure

11,900 lb.
6,700 lb.



FIG 113
SERIES 2C
SAND BALLAST 30 INCHES DEEP
21 INCH CIRCULAR PLATE

Distance from Center of Load - inches.

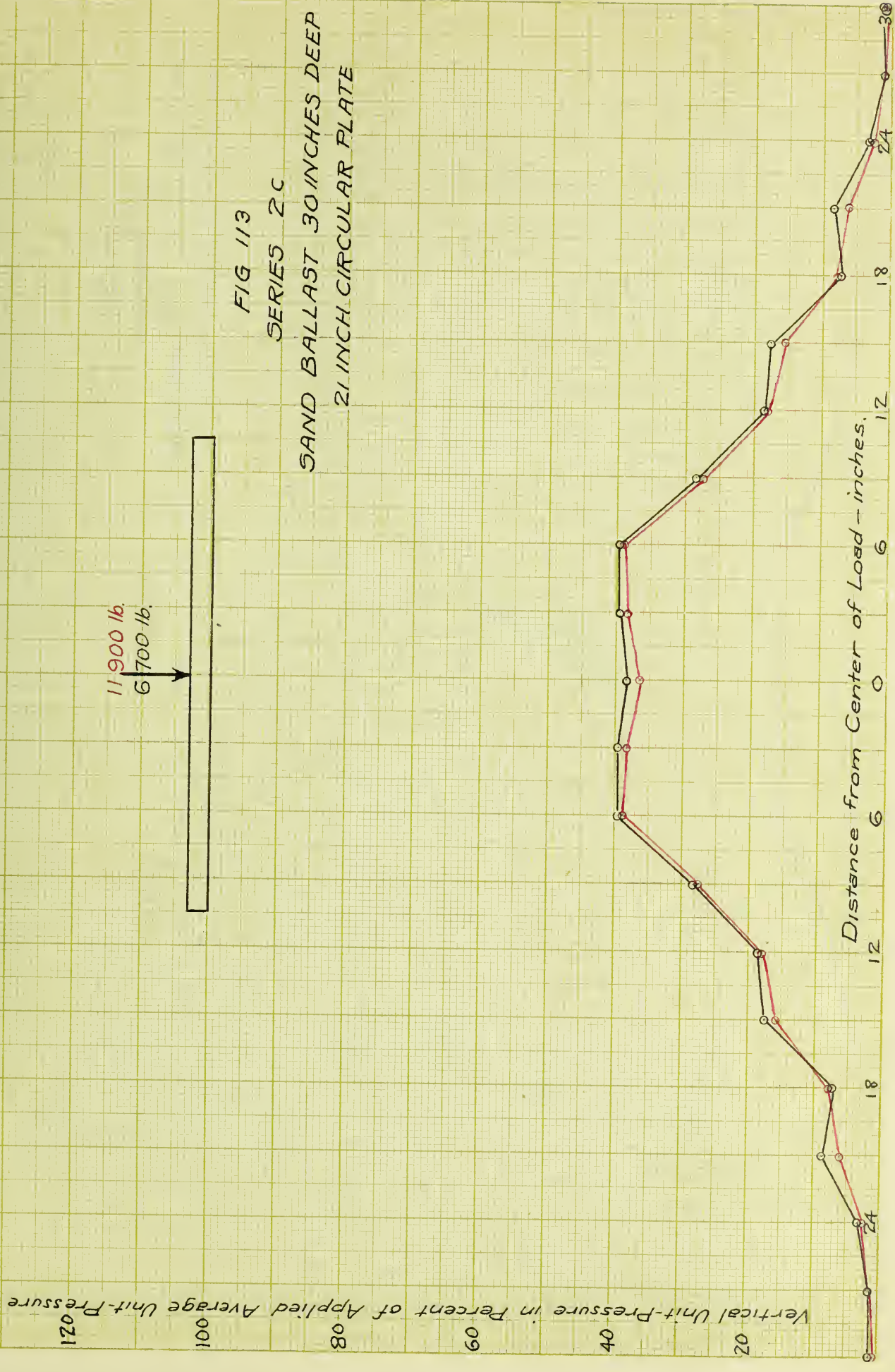
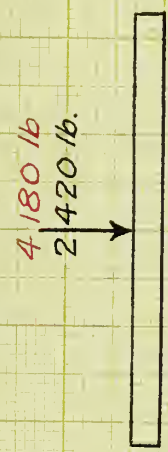
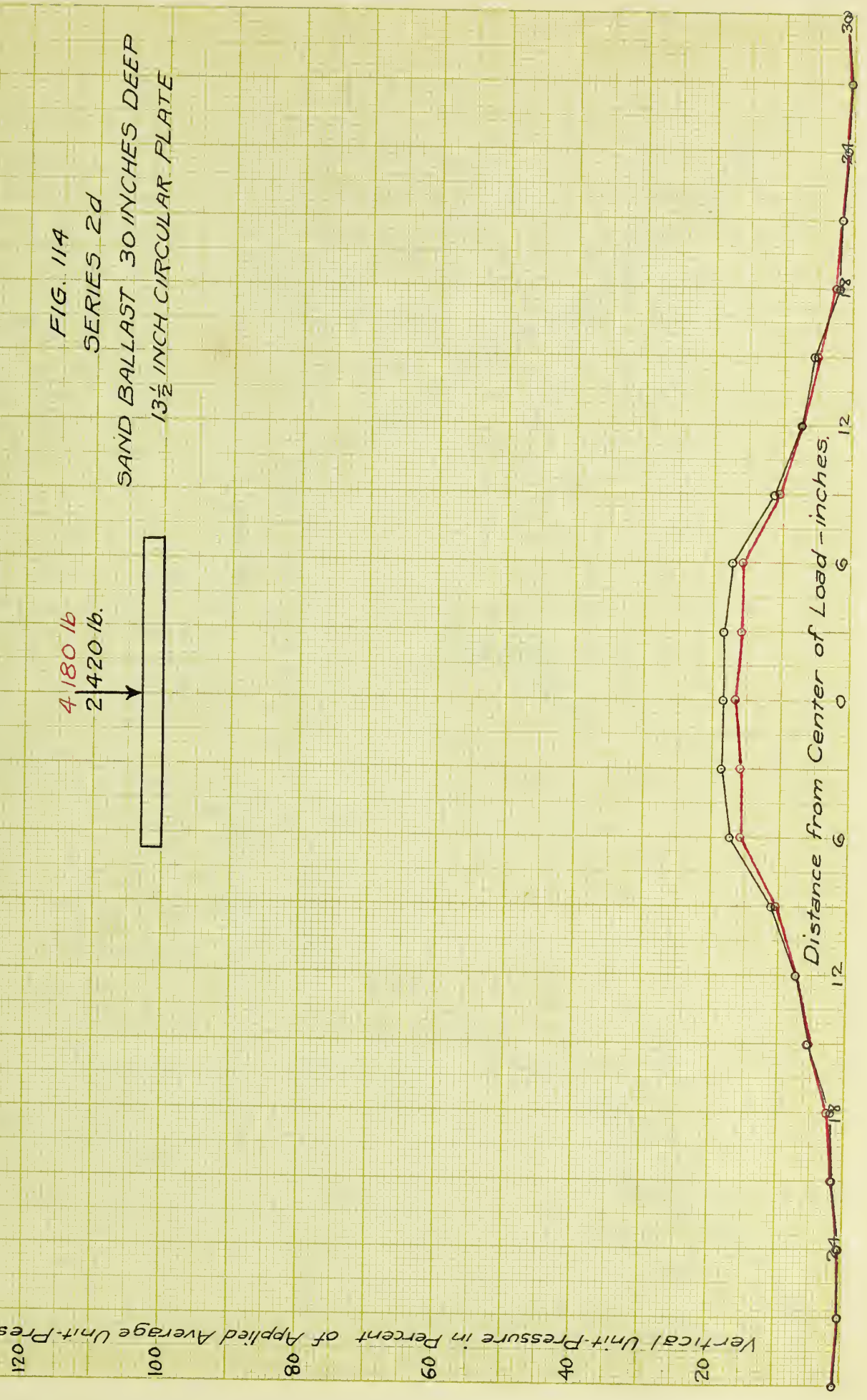


FIG. 114
SERIES 2d
SAND BALLAST 30 INCHES DEEP
13 1/2 INCH CIRCULAR PLATE



Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

Distance from Center of Load-inches.



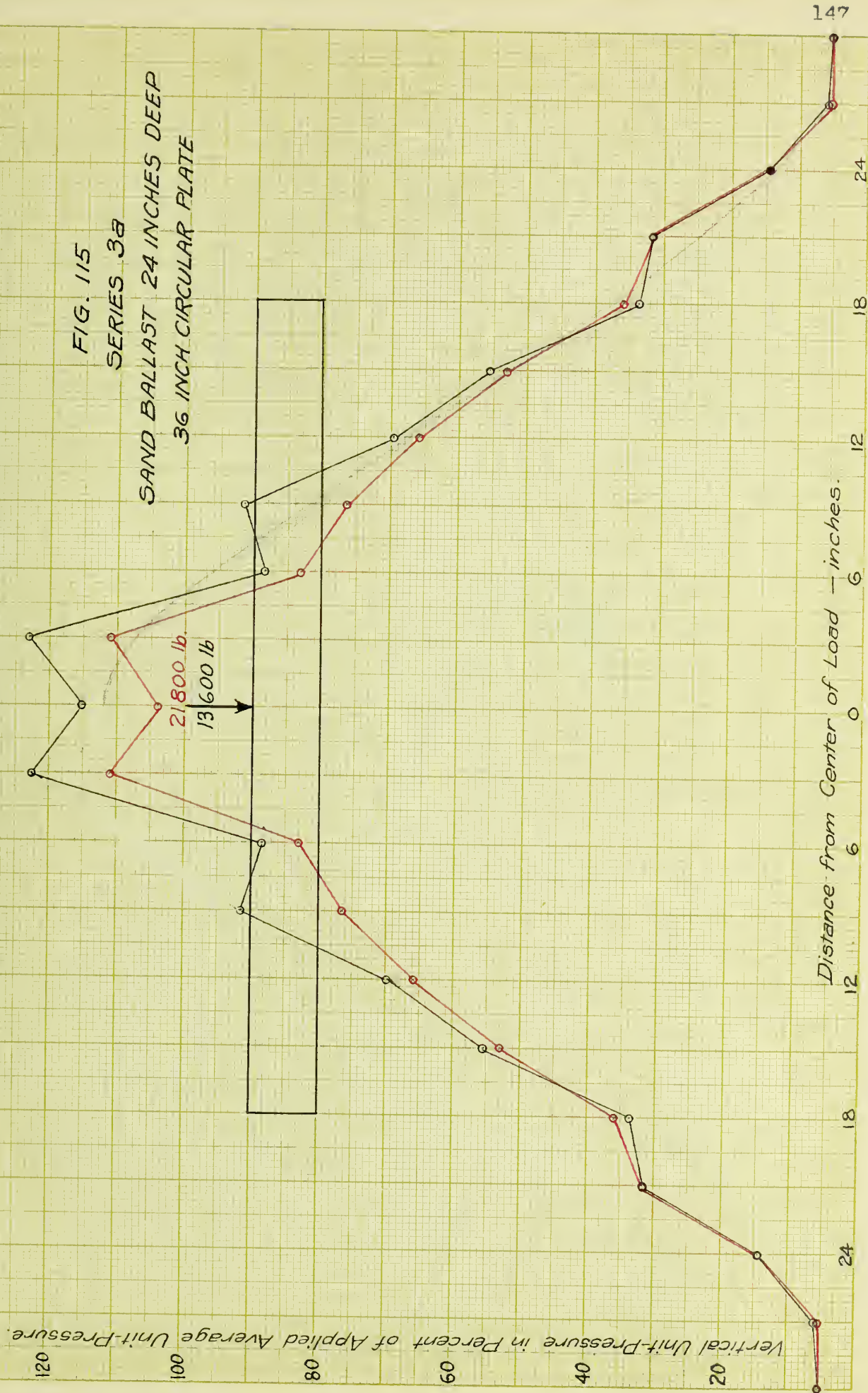
Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

FIG. 115
SERIES 3a

SAND BALLAST 24 INCHES DEEP
36 INCH CIRCULAR PLATE

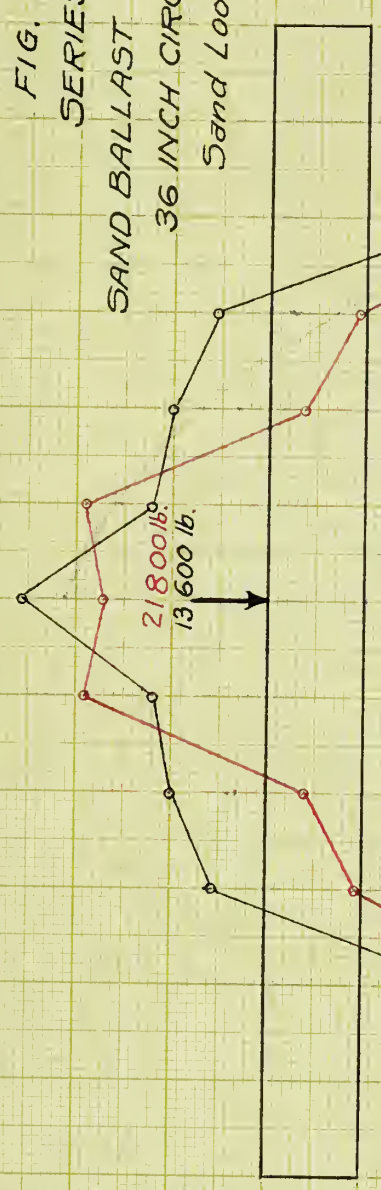
21,800 lb.
13,600 lb.

Distance from Center of Load - inches.

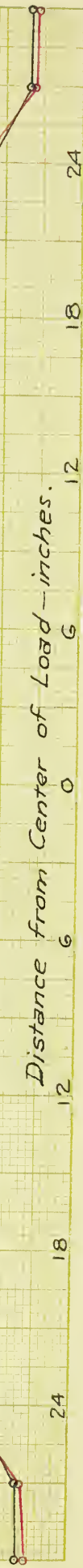


Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

FIG. 116
 SERIES 3a'
 SAND BALLAST 24 INCHES DEEP
 36 INCH CIRCULAR PLATE
 Sand Loosened

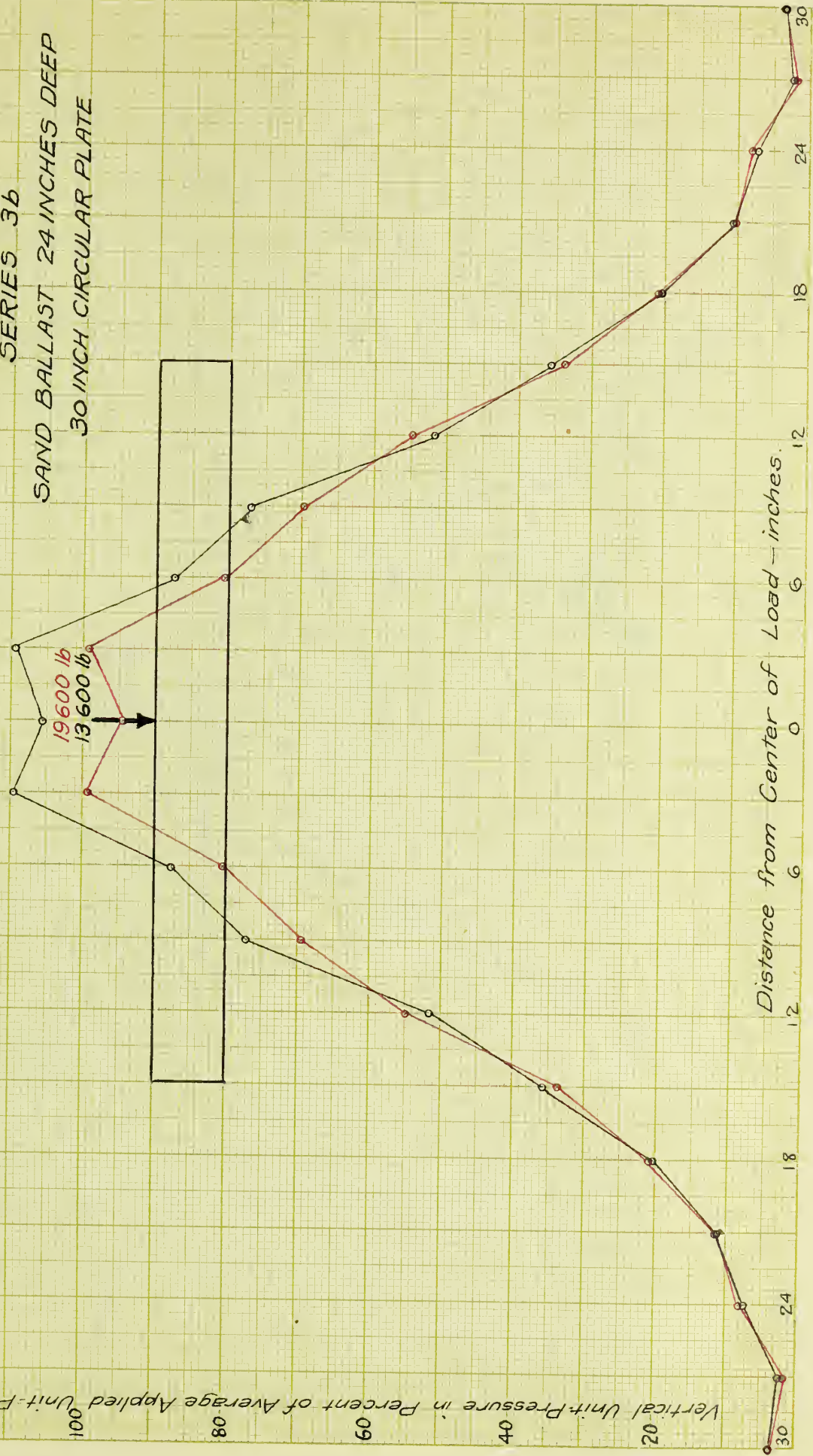


Distance from Center of Load—inches.



Vertical Unit Pressure in Percent of Average Applied Unit Pressure.

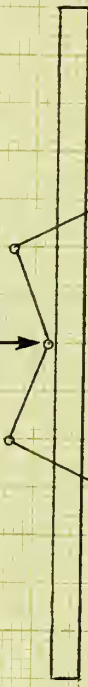
FIG 117
 SERIES 3b
 SAND BALLAST 24 INCHES DEEP
 30 INCH CIRCULAR PLATE



Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

FIG. 118
 SERIES 3C
 SAND BALLAST 24-INCHES DEEP
 21 INCH CIRCULAR PLATE

13 600 lb.
 6 700 lb.



Distance from Center of Load - inches.

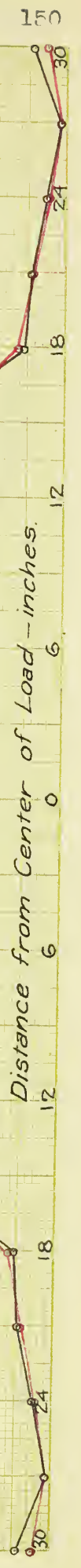
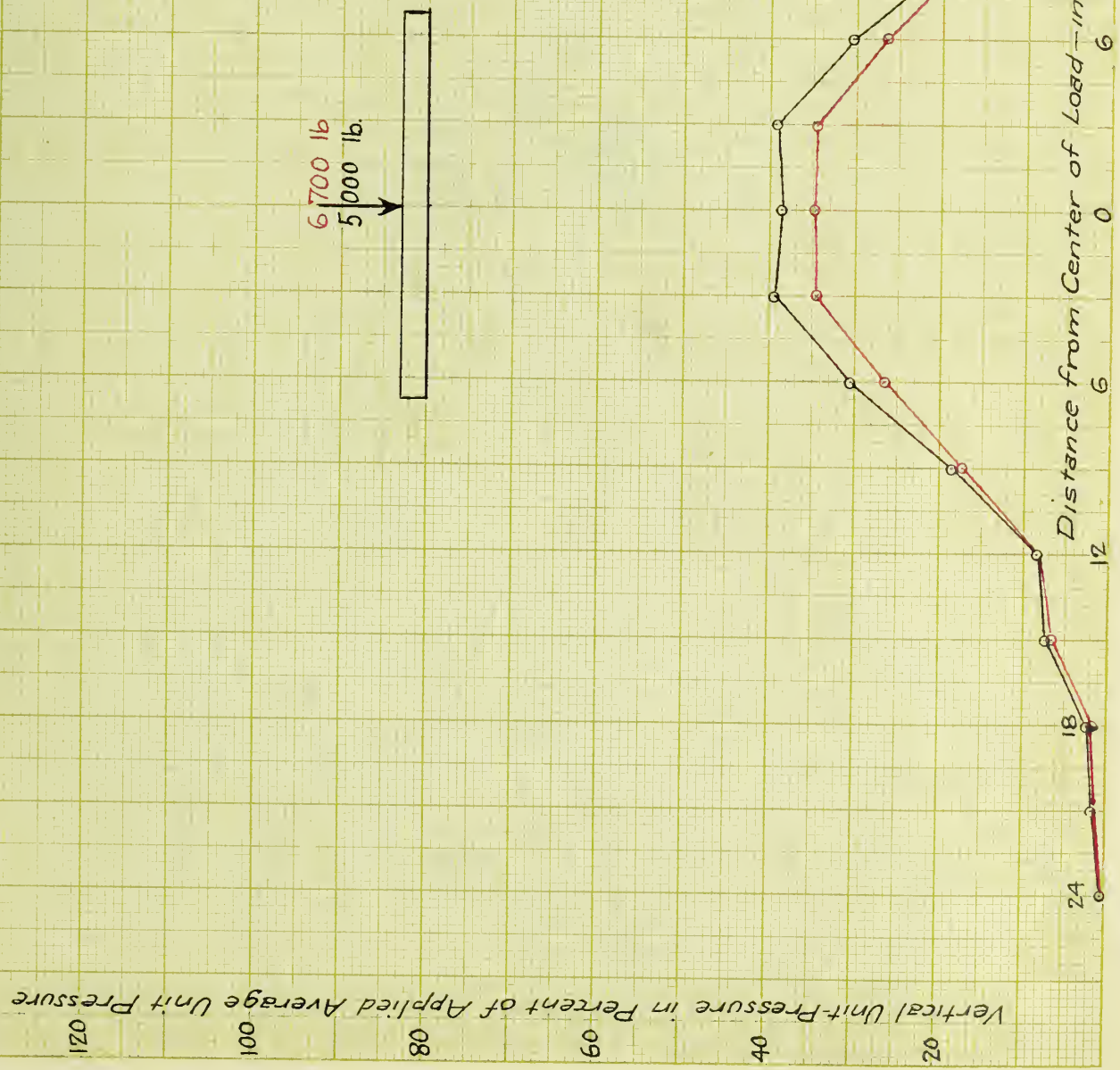
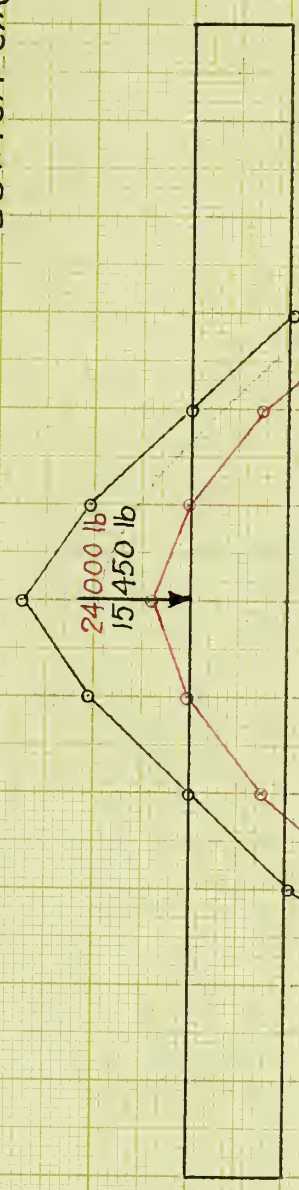


FIG. 119
SERIES 3d
SAND BALLAST 24 INCHES DEEP
13½ INCH CIRCULAR PLATE



Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure

FIG. 120
 SERIES 4a
 SAND BALLAST 18 INCHES DEEP
 36 INCH CIRCULAR PLATE



24,000 lb
 15,450 lb

Distance from Center of Load-inches.

260

240

220

200

180

160

140

120

100

80

60

40

20

0

24

24

18

12

6

0

6

12

18

24

FIG. 121
 SERIES 4b
 SAND BALLAST 18 INCHES DEEP
 30 INCH CIRCULAR PLATE

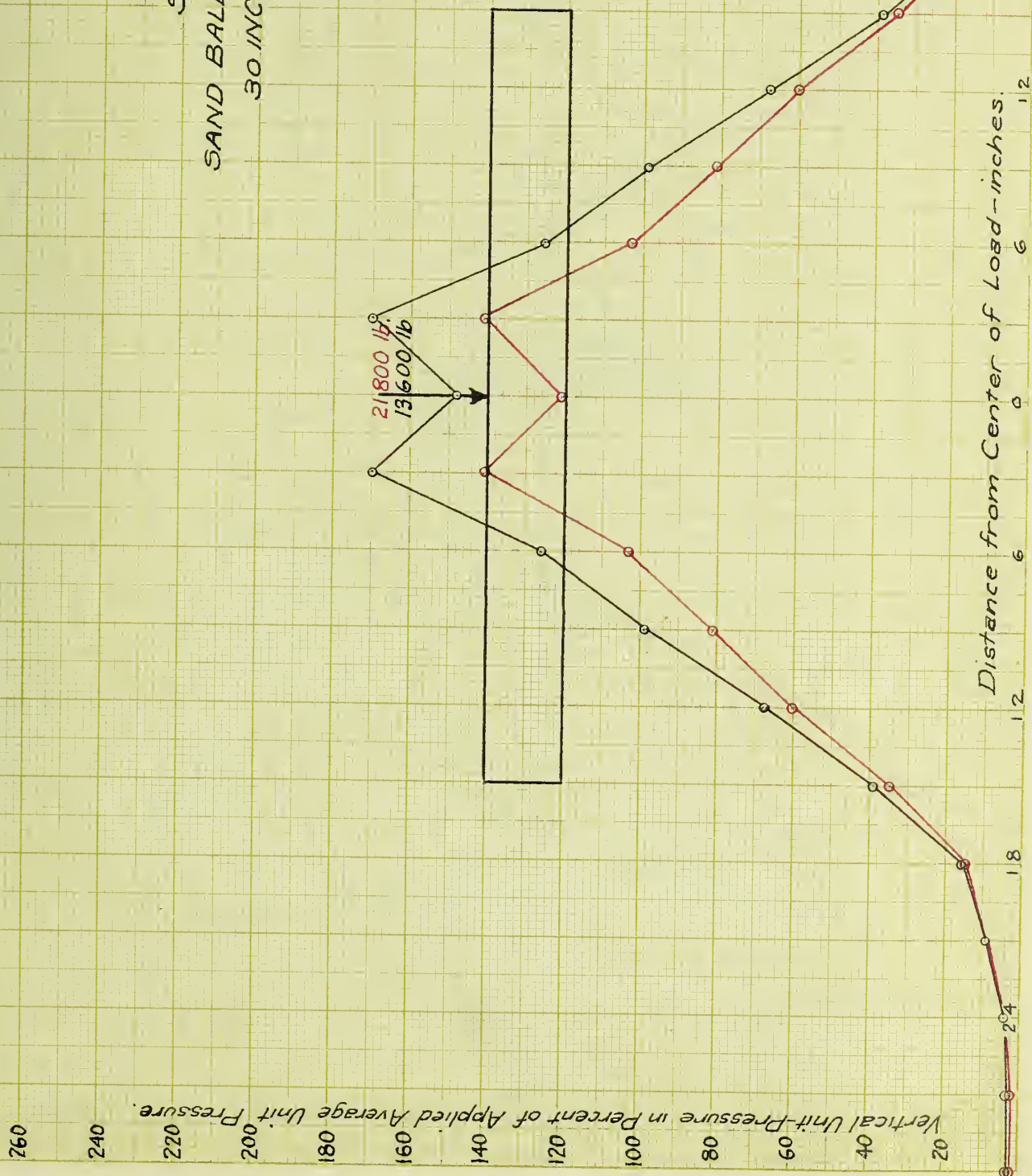


FIG. 122
 SERIES 4c
 SAND BALLAST 18 INCHES DEEP
 21 INCH CIRCULAR PLATE

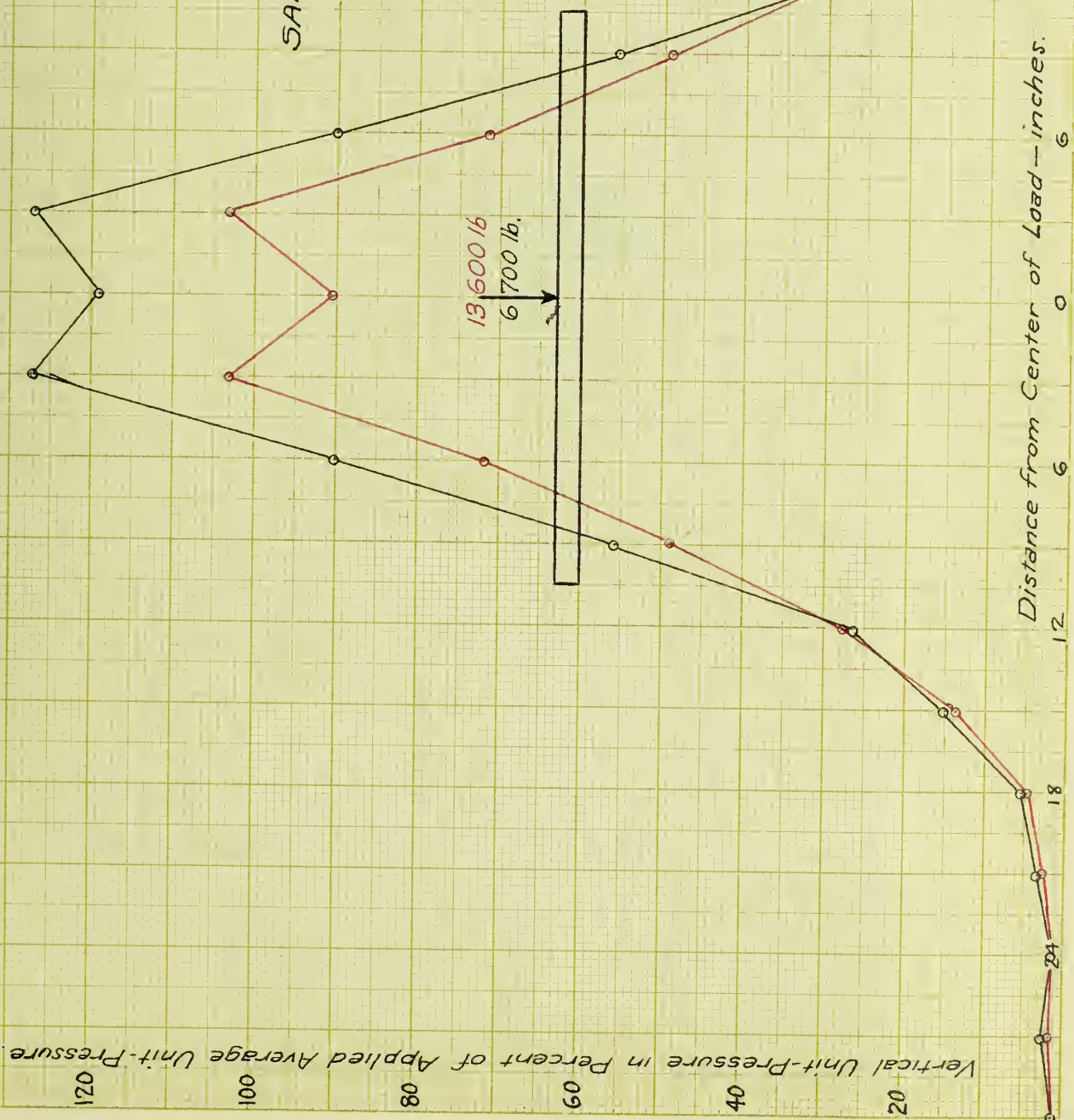


FIG. 123
 SERIES 4d
 SAND BALLAST 18 INCHES DEEP
 13½ INCH CIRCULAR PLATE

120

Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure

1000

80

60

40

20

6700 lb.

3280 lb.



Distance from Center of Pressure-inches.

0

6

12

18

24

30

12

18

24

30

42

54

66

78

90

102

FIG. 124
 SERIES 5a
 SAND BALLAST 12 INCHES DEEP
 36 INCH CIRCULAR PLATE

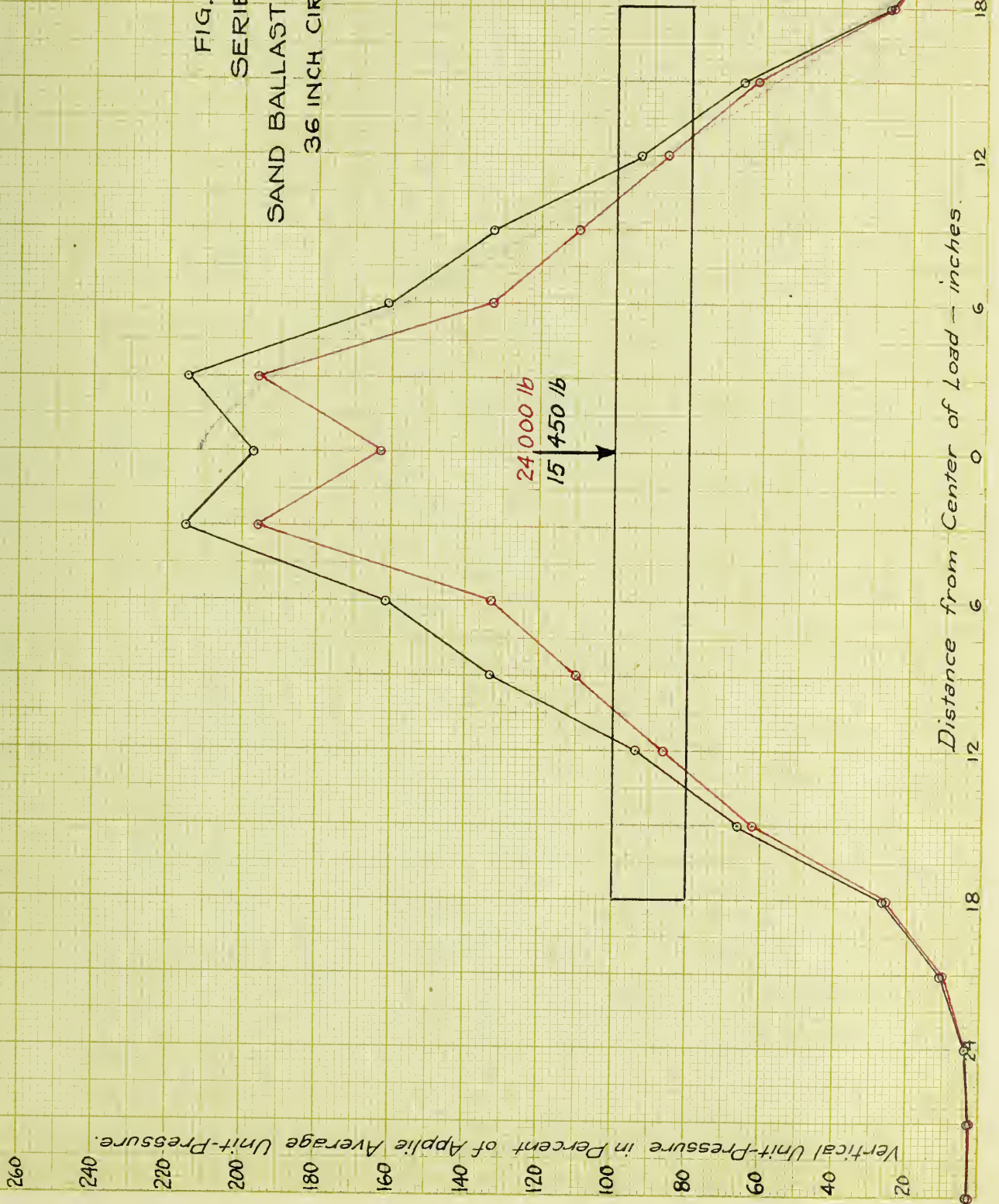


FIG. 125
 SERIES 5b
 SAND BALLAST 12 INCHES DEEP
 30 INCH CIRCULAR PLATE

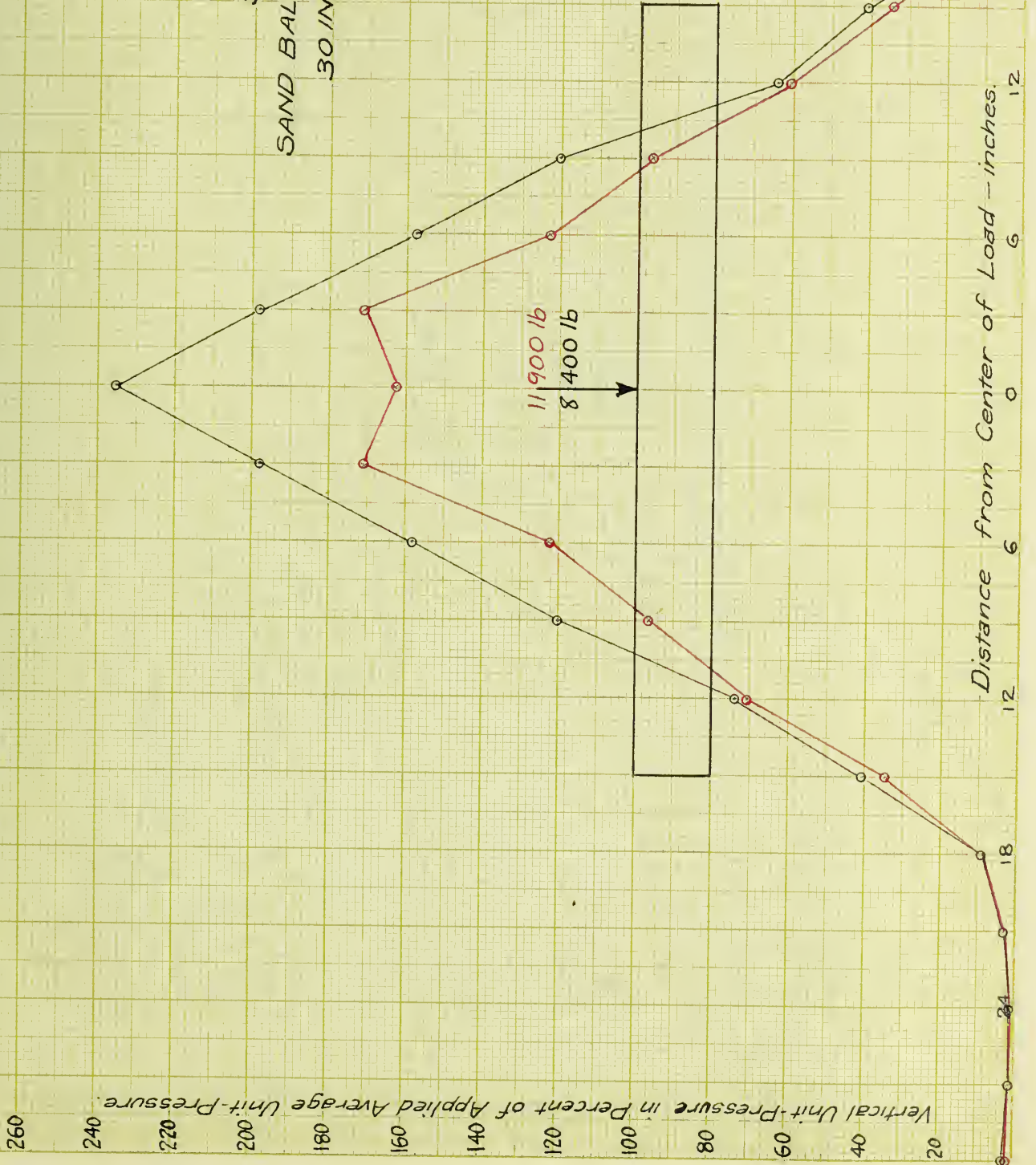
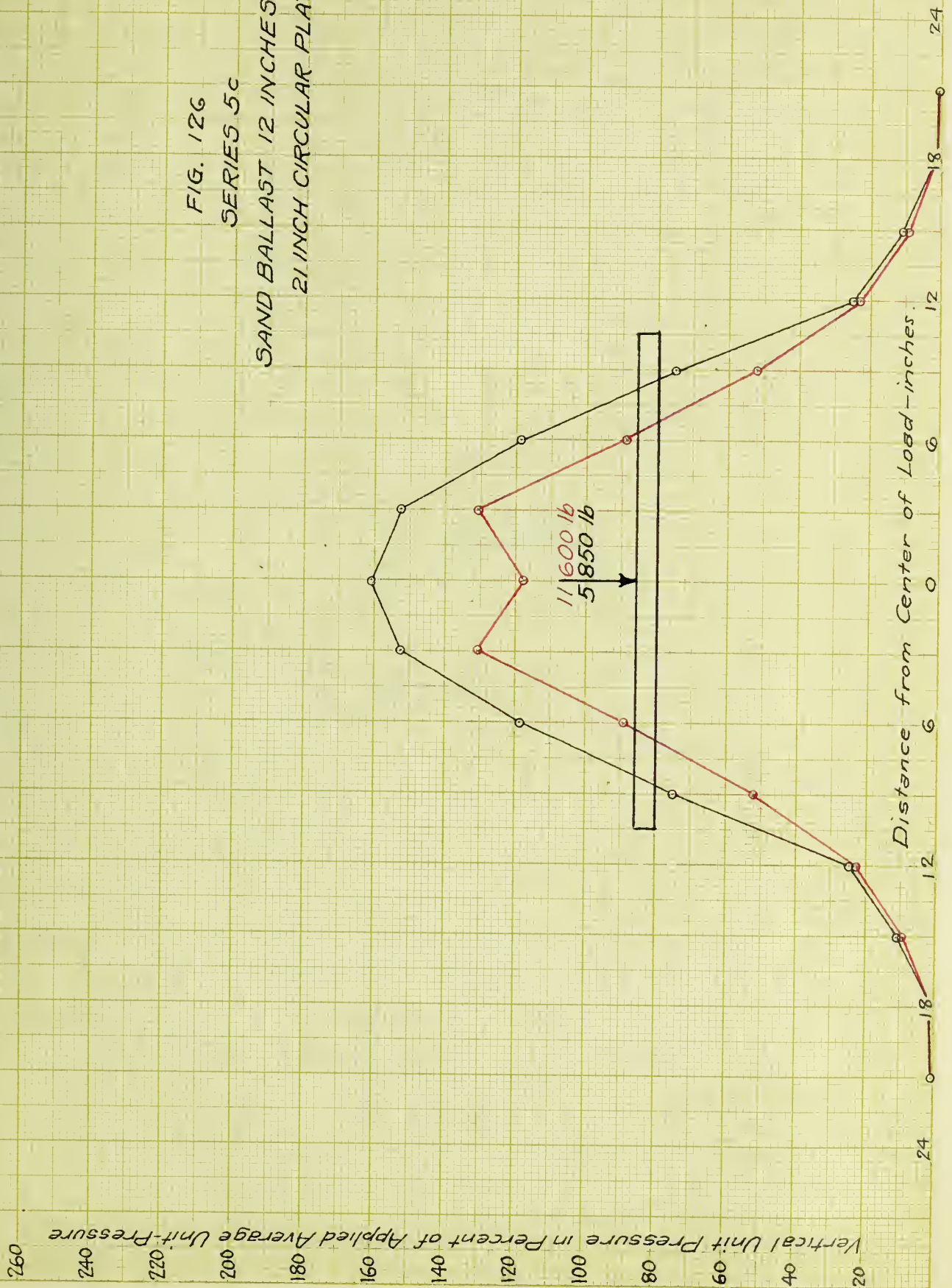


FIG. 126
 SERIES 5c
 SAND BALLAST 12 INCHES DEEP
 21 INCH CIRCULAR PLATE



Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure

FIG. 127
 SERIES 5d
 SAND BALLAST 12 INCHES DEEP
 13 1/2 INCH CIRCULAR PLATE

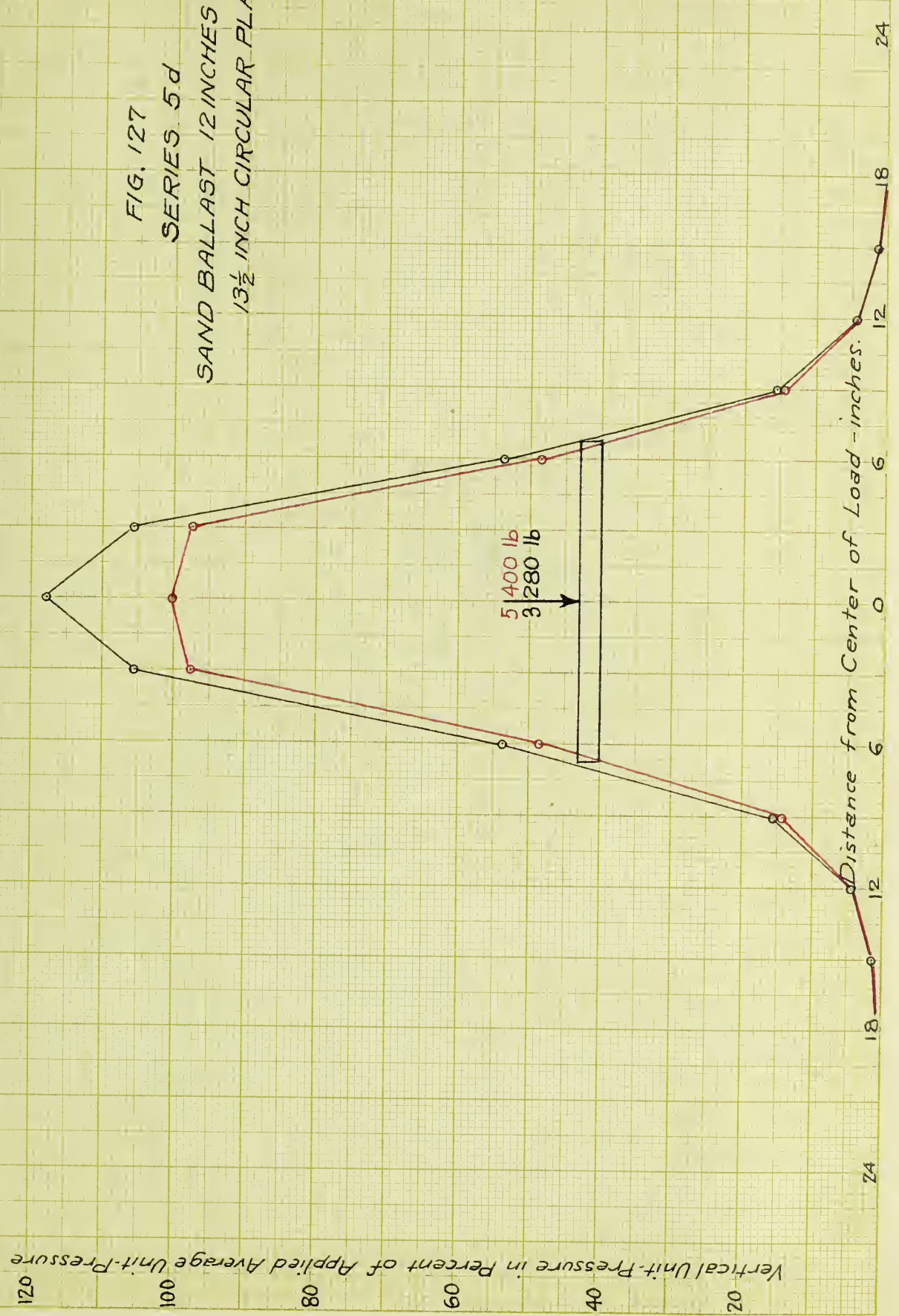


FIG. 128
 SERIES 5d'
 SAND BALLAST 12 IN. DEEP
 13½ IN. CIRCULAR PLATE

Vertical Unit-Pressure in Percent of Applied Average Unit-Pressure.

120

100

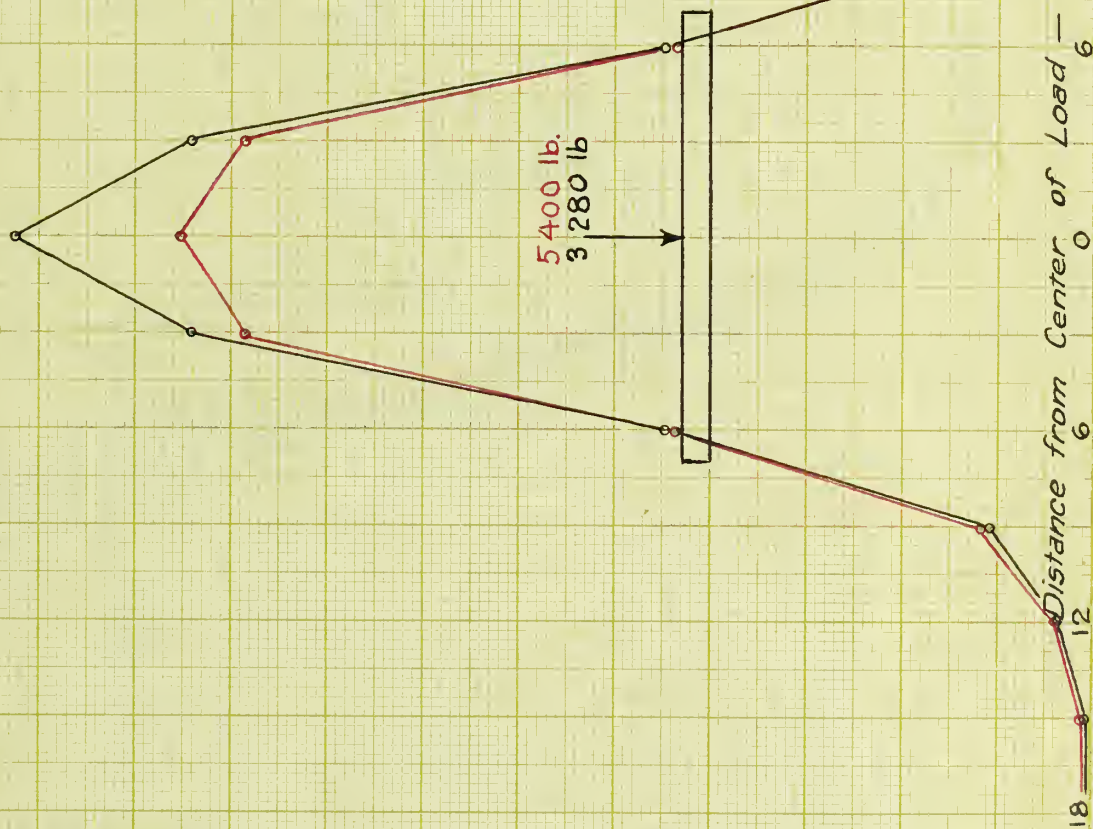
80

60

40

20

30



5400 lb.
 3280 lb.

Distance from Center of Load — inches

18

24

30

12

6

0

6

12

18

24

30

Vertical Unit Pressure in Percent of Applied Average Unit Pressure

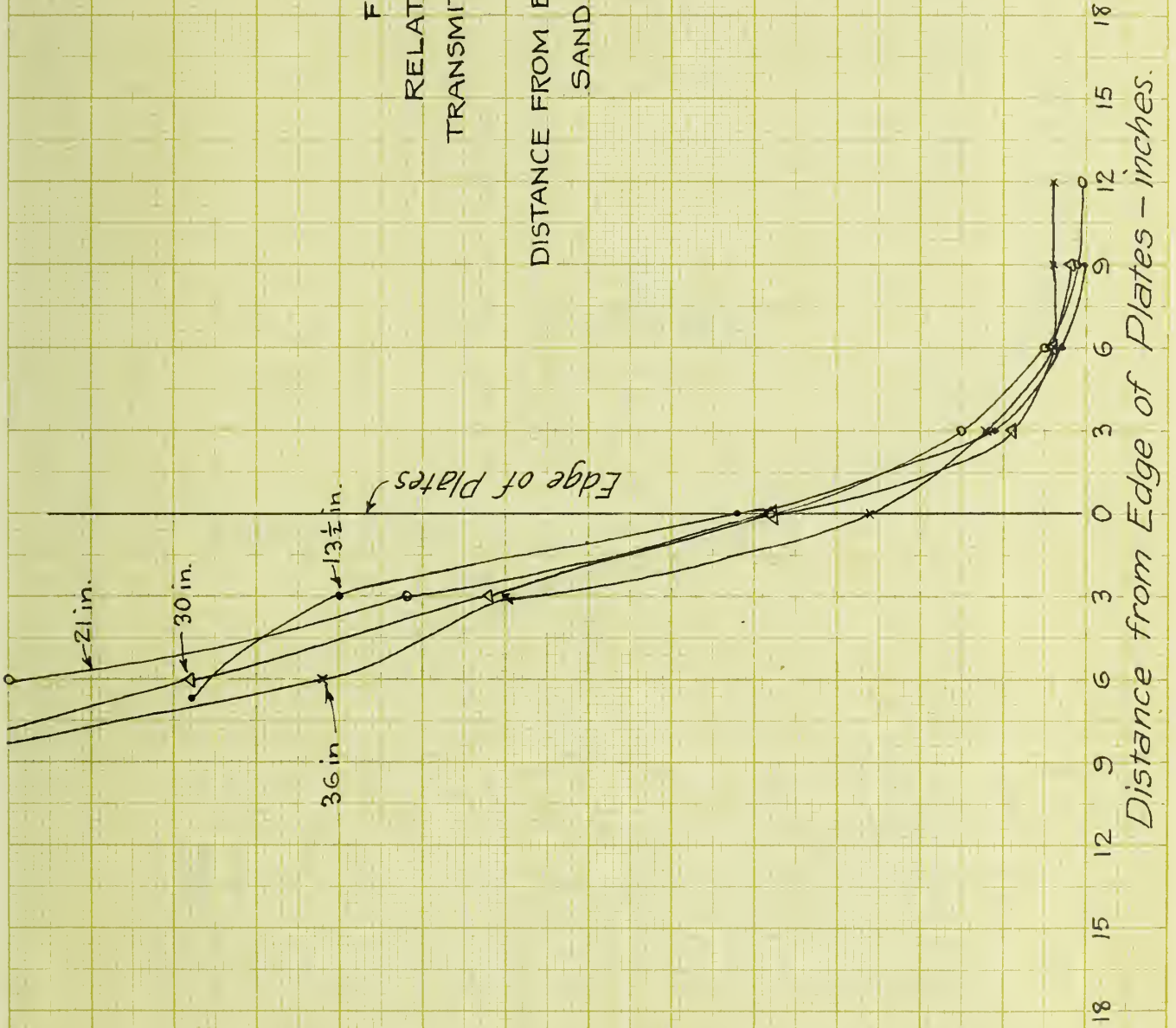
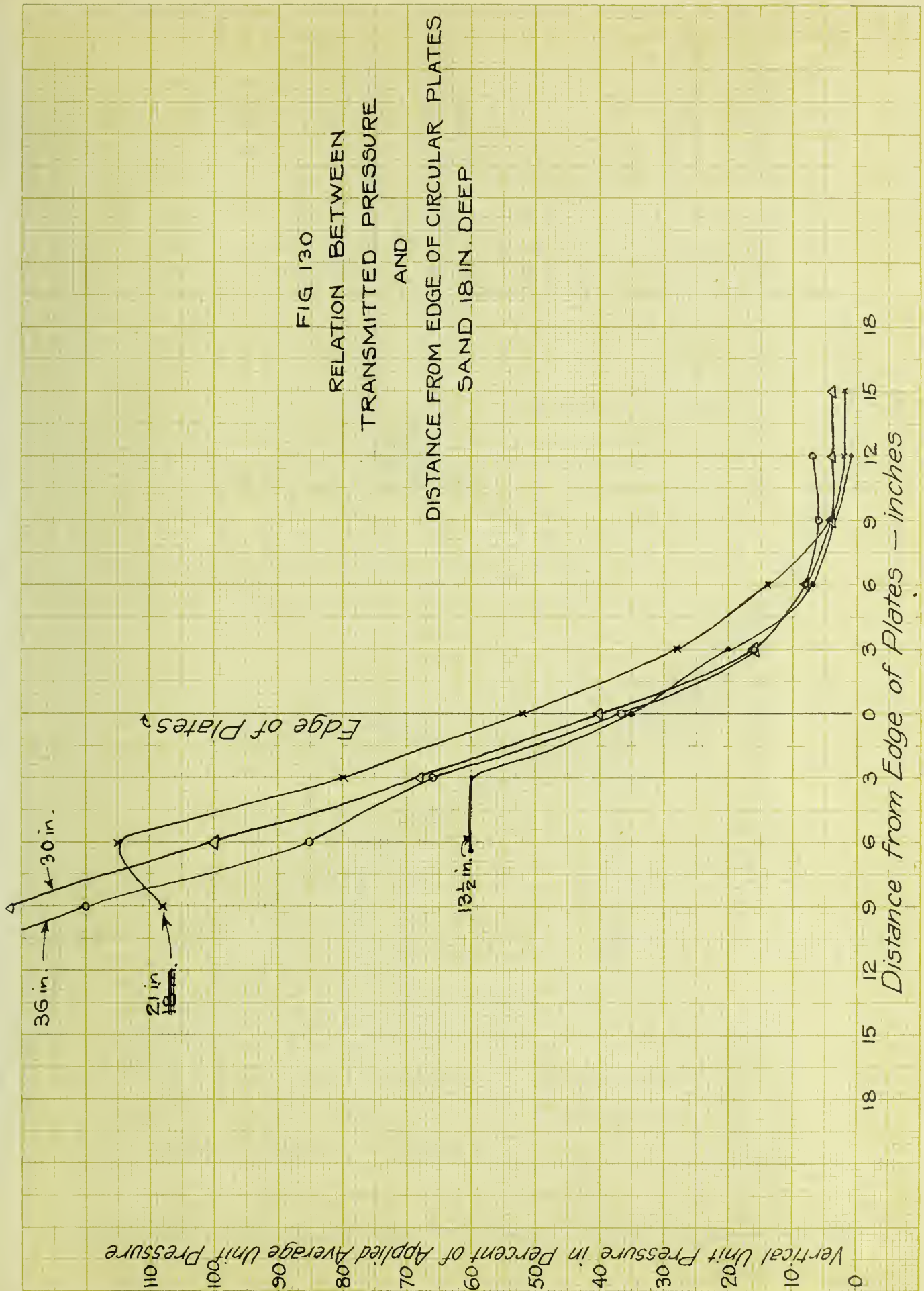


FIG. 129
RELATION BETWEEN
TRANSMITTED PRESSURE
AND
DISTANCE FROM EDGE OF CIRCULAR PLATES
SAND 12 IN. DEEP

1240
1875-1900



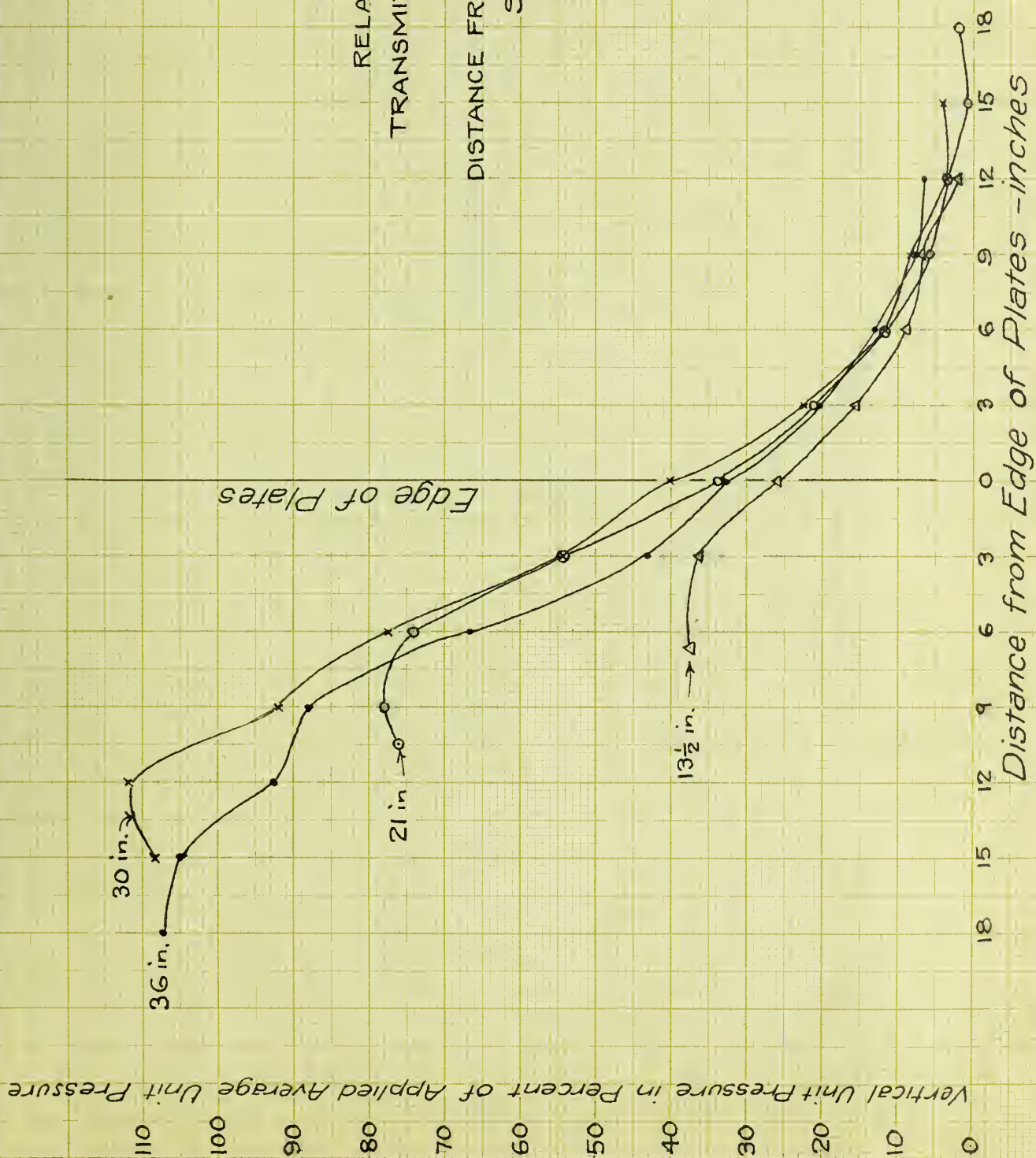


FIG. 131

RELATION BETWEEN
TRANSMITTED PRESSURE
AND

DISTANCE FROM EDGE OF CIRC. PLATES
SAND 24 IN. DEEP

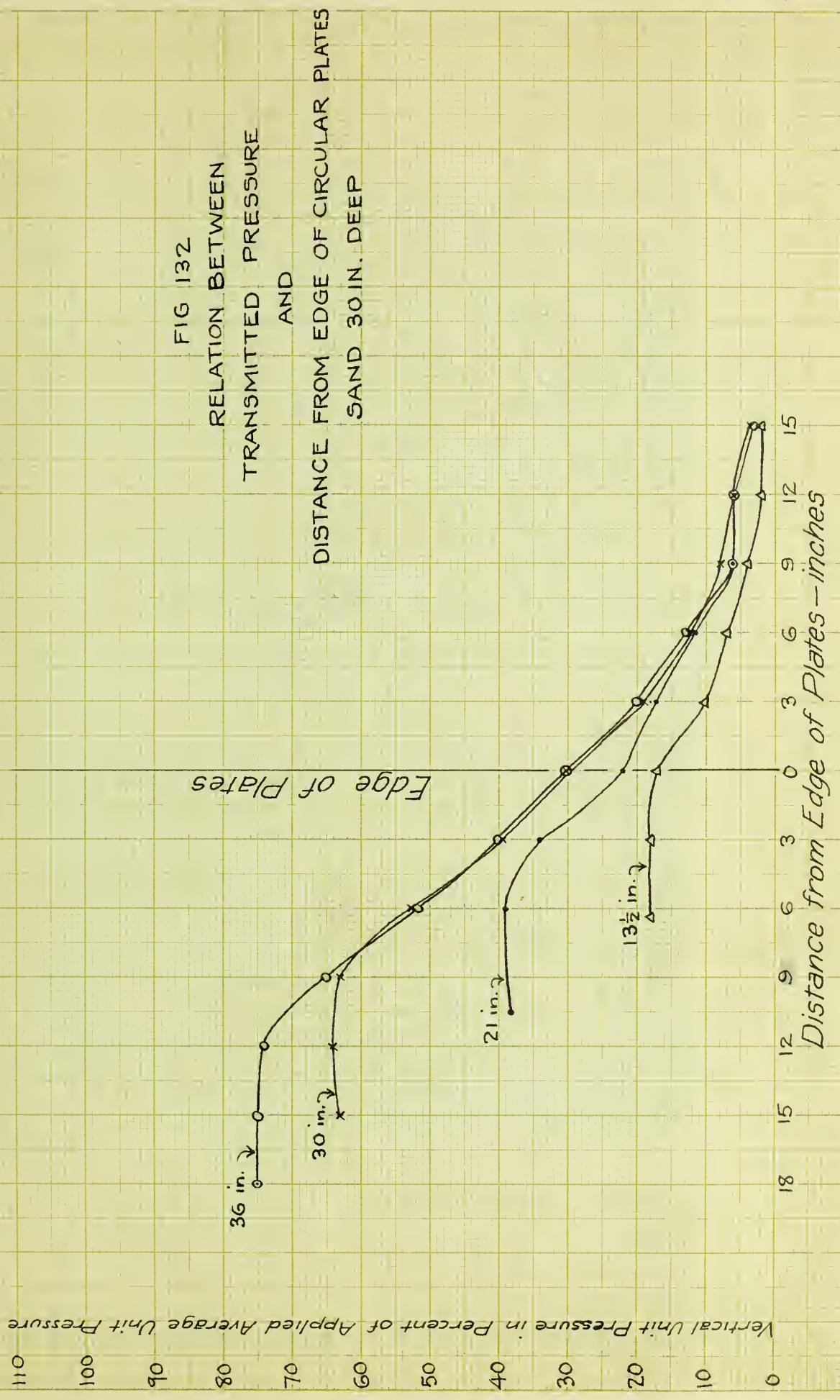


FIG 132
RELATION BETWEEN
TRANSMITTED PRESSURE
AND
DISTANCE FROM EDGE OF CIRCULAR PLATES
SAND 30 IN. DEEP

Vertical Unit Pressure in Percent of Applied Average Unit Pressure.

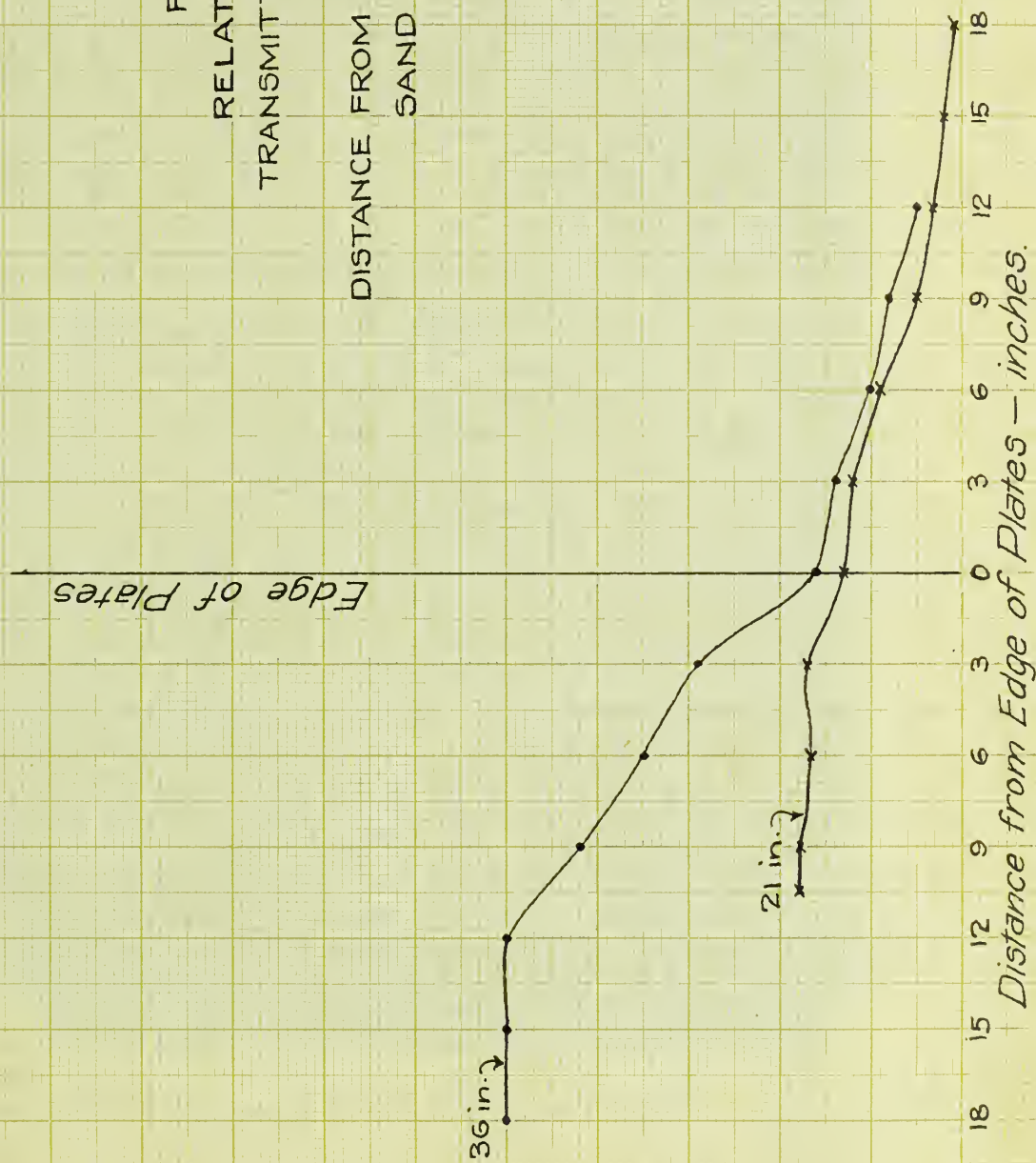


FIG. 133

RELATION BETWEEN
TRANSMITTED PRESSURE
AND

DISTANCE FROM EDGE OF CIRCULAR PLATES
SAND 38 IN. DEEP

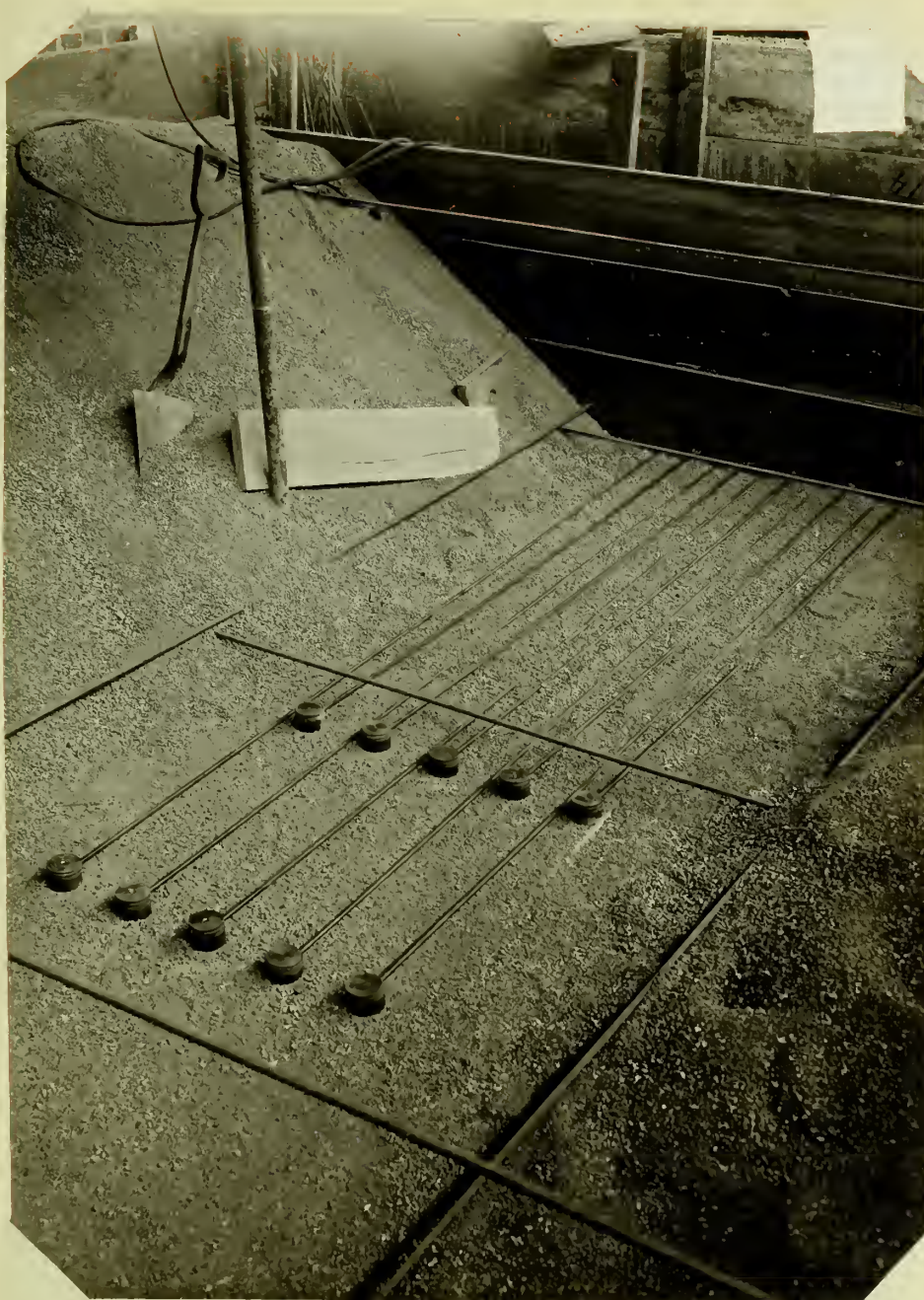


Fig. 134. Arrangement of Pressure Capsules for Series A.



Fig. 135. Arrangement of Apparatus for Series A.

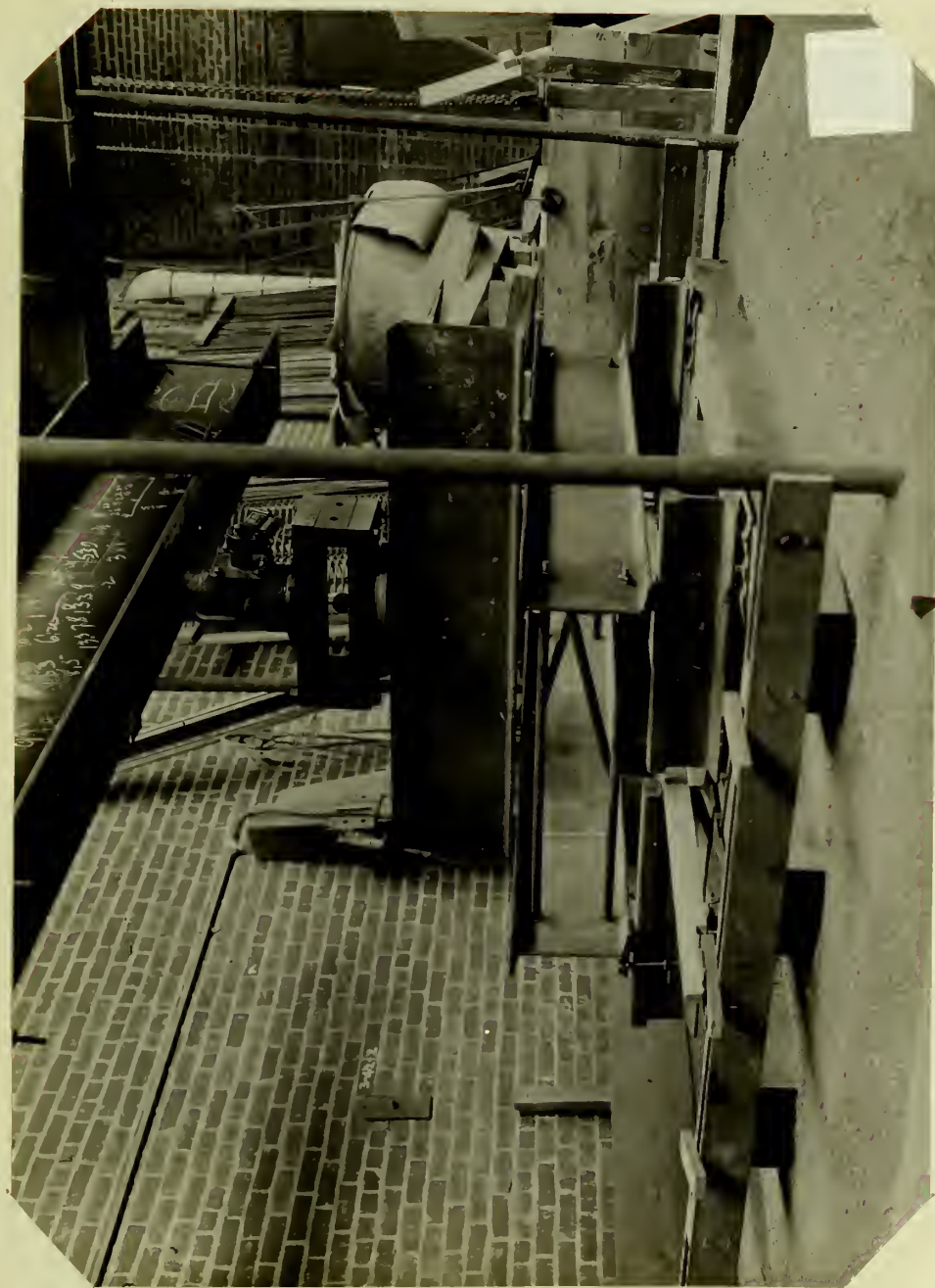


Fig 136. Arrangement for Loading Three Ties.

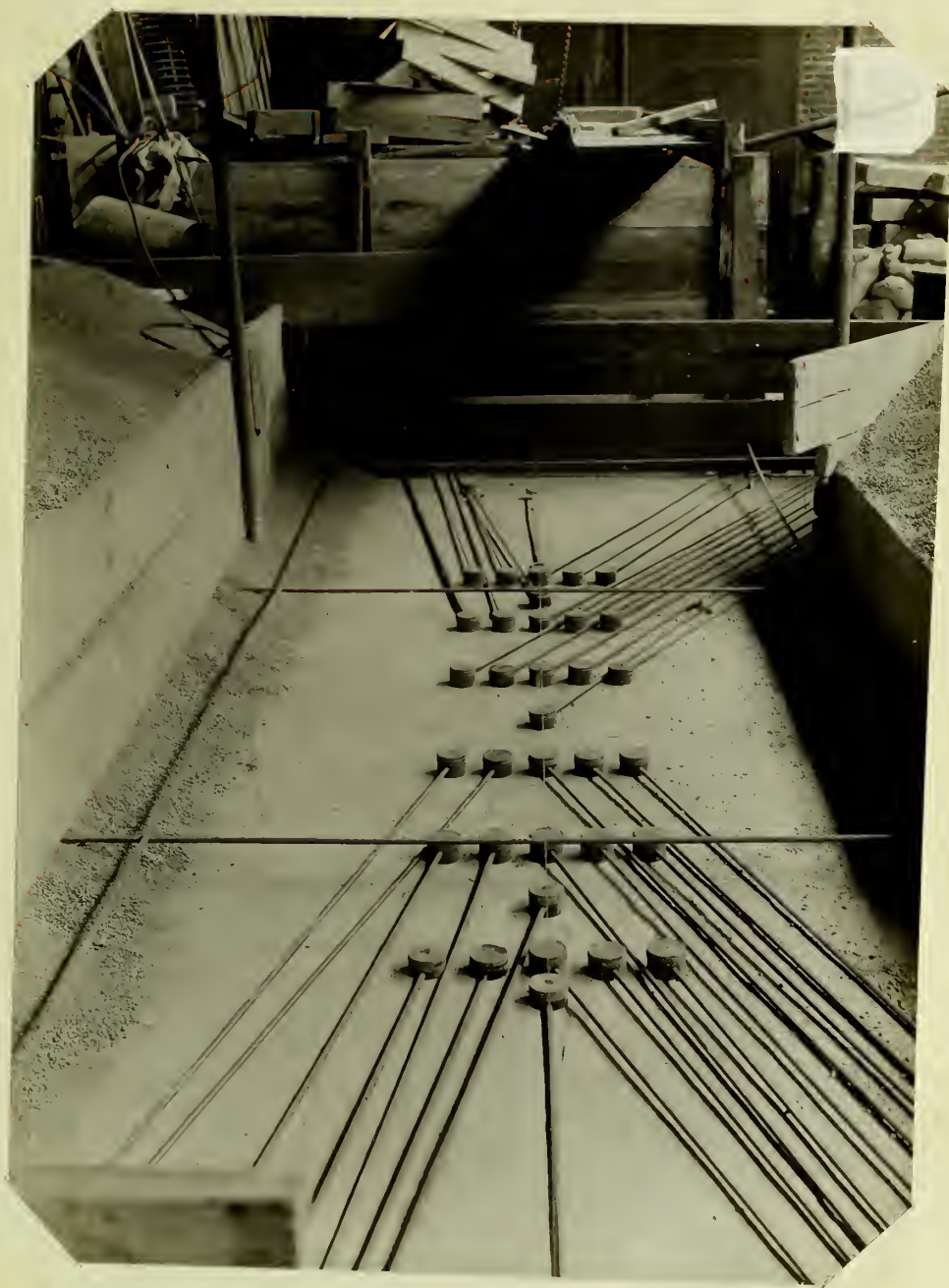


Fig. 137. Capsules in Place Ready to be Covered with Sand, Series R.



Fig. 138. Capsules placed on Sand Cushion - Rock Ballast Experiments.



Fig. 139. Experiments with Gravel Ballast.

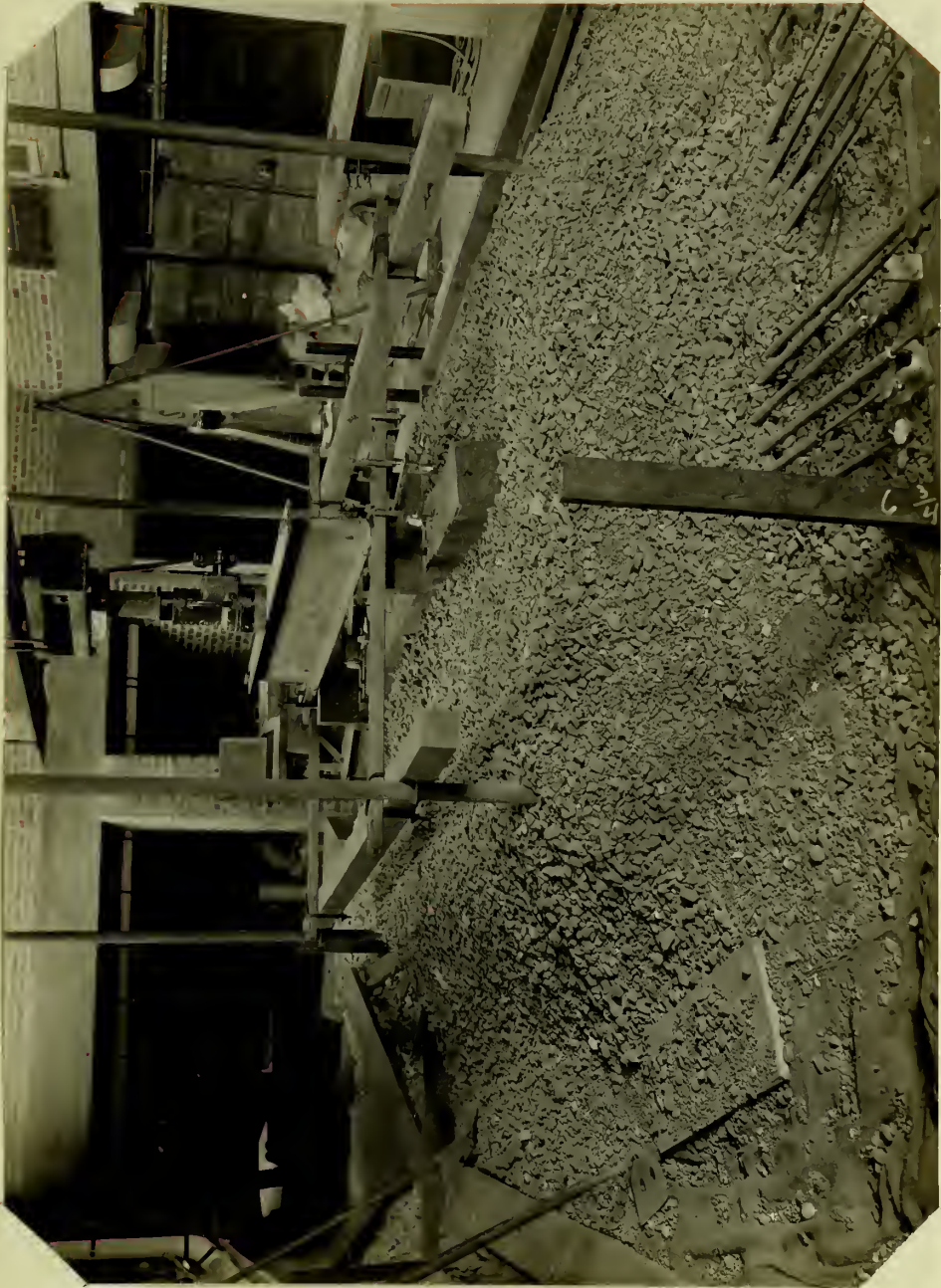


Fig. 140. Experiments with Gravel Ballast.

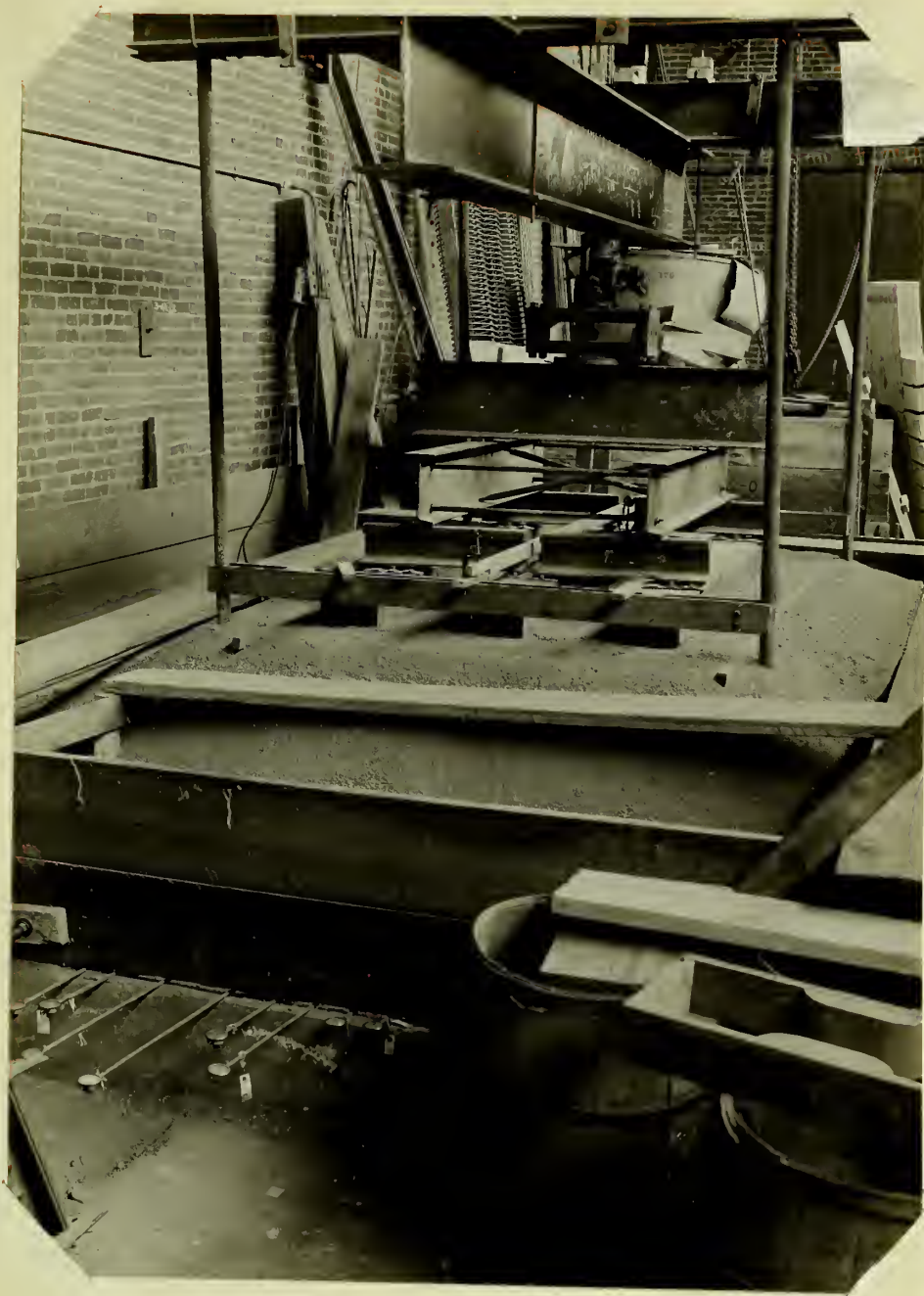


Fig. 141. Sand Ballast Experiments, Arrangement for Loading Three Ties.



Fig. 142. Gravel Ballast Experiments. Note 1-inch
pipes the protect the the pipes from the capsules.

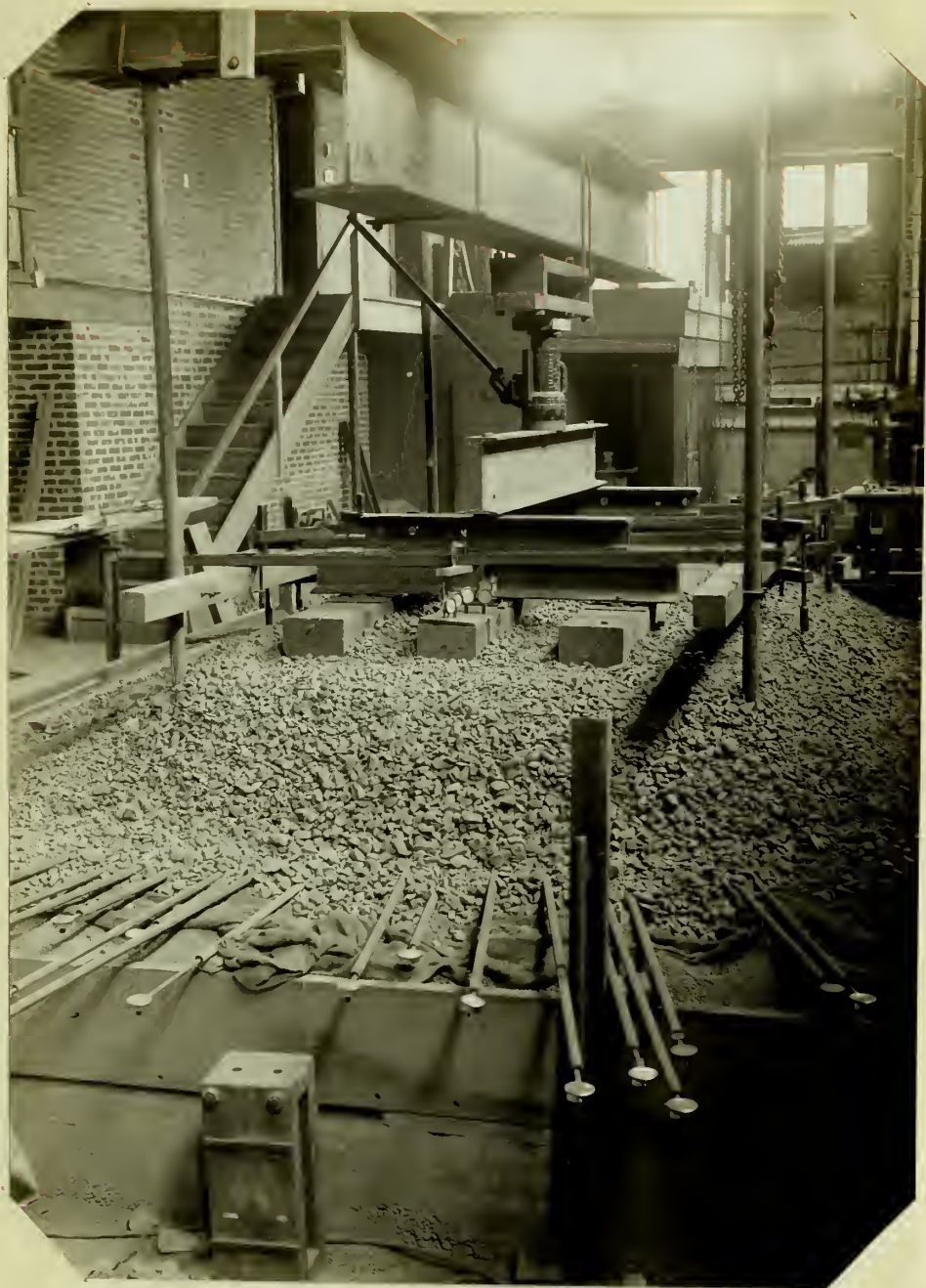


Fig. 143. Gravel Ballast Experiments. Series A4.

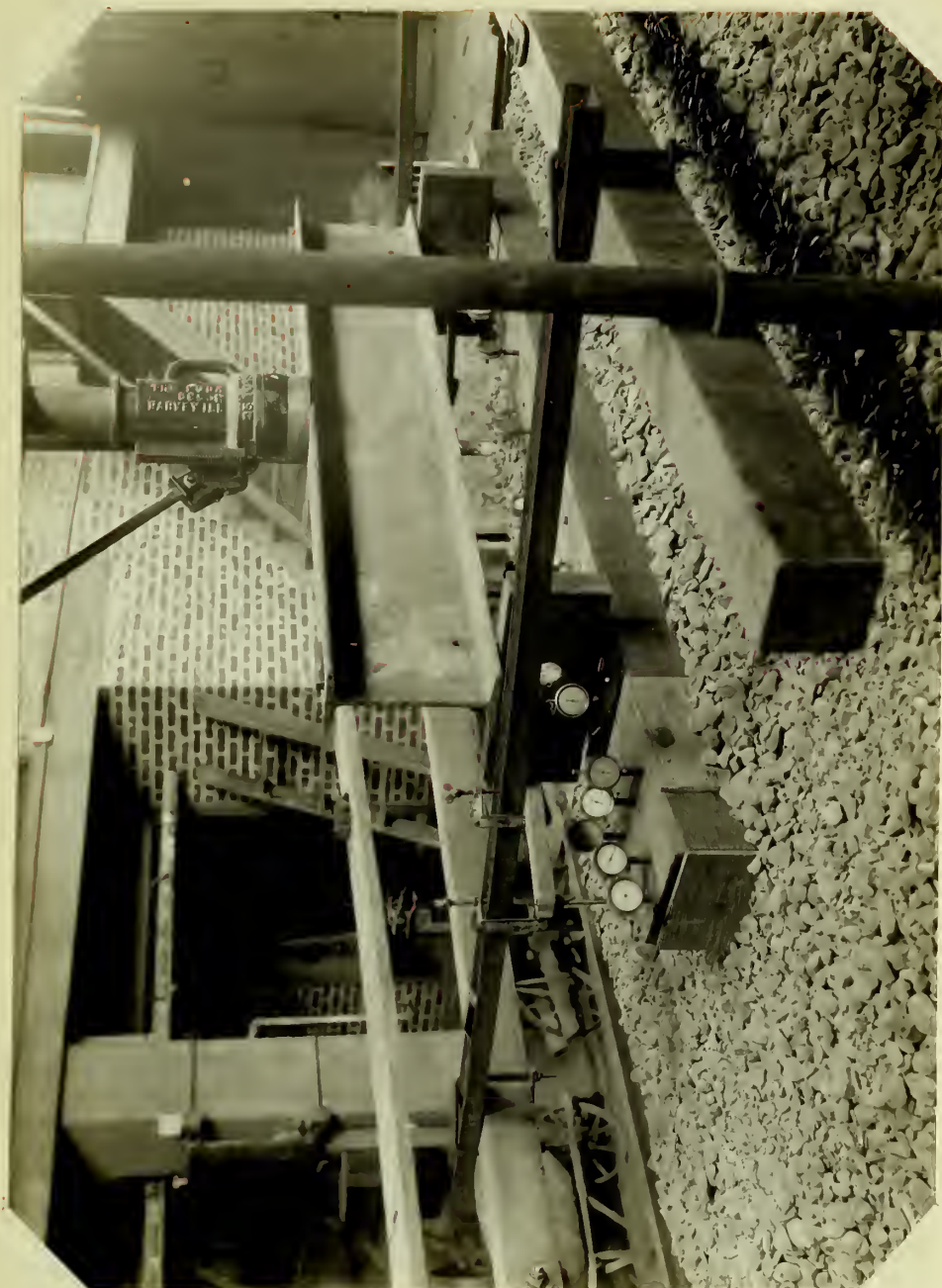


Fig. 144. Gravel Ballast. Experiment to Determine Pressure on bottom of Tie.

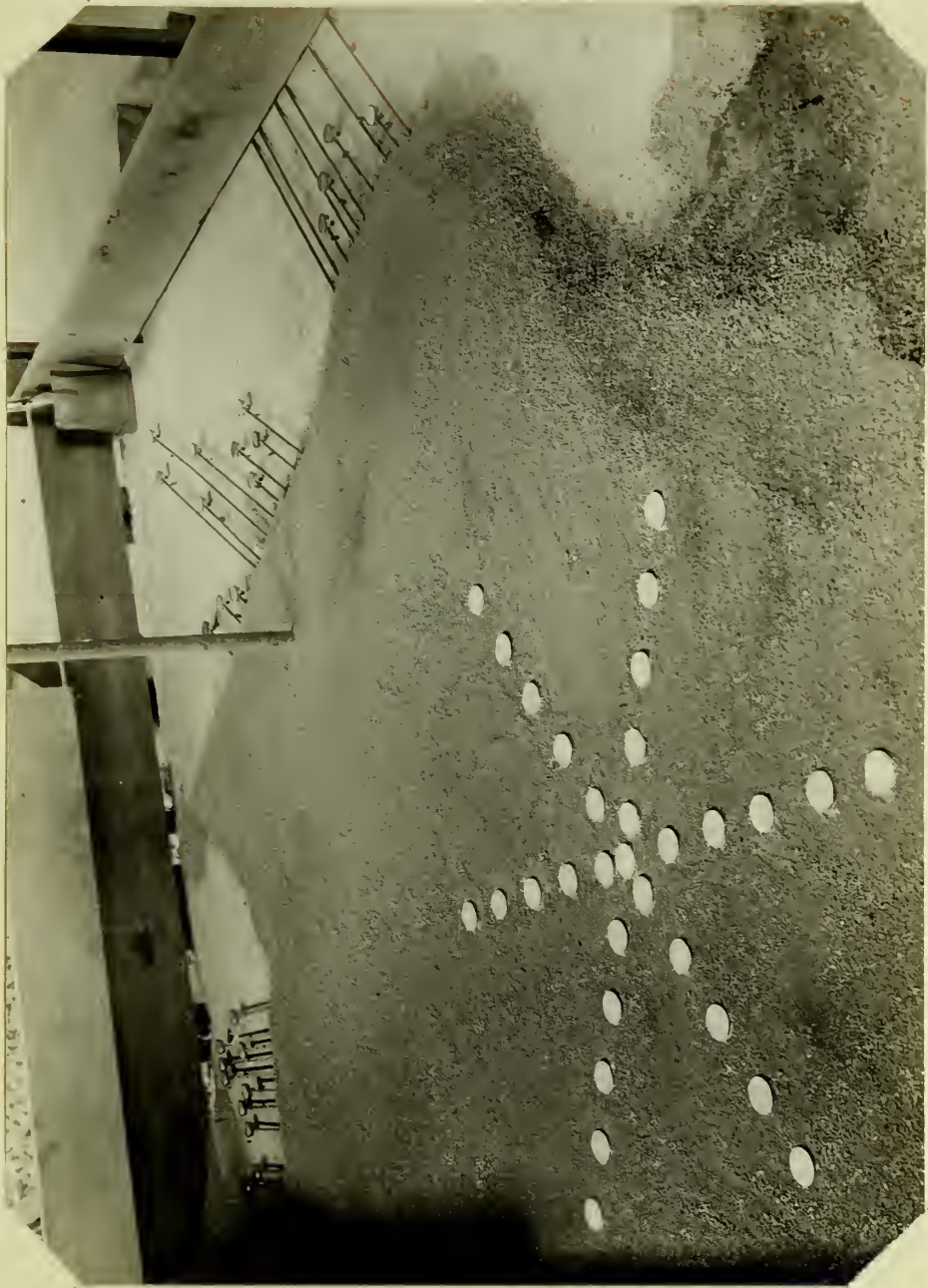
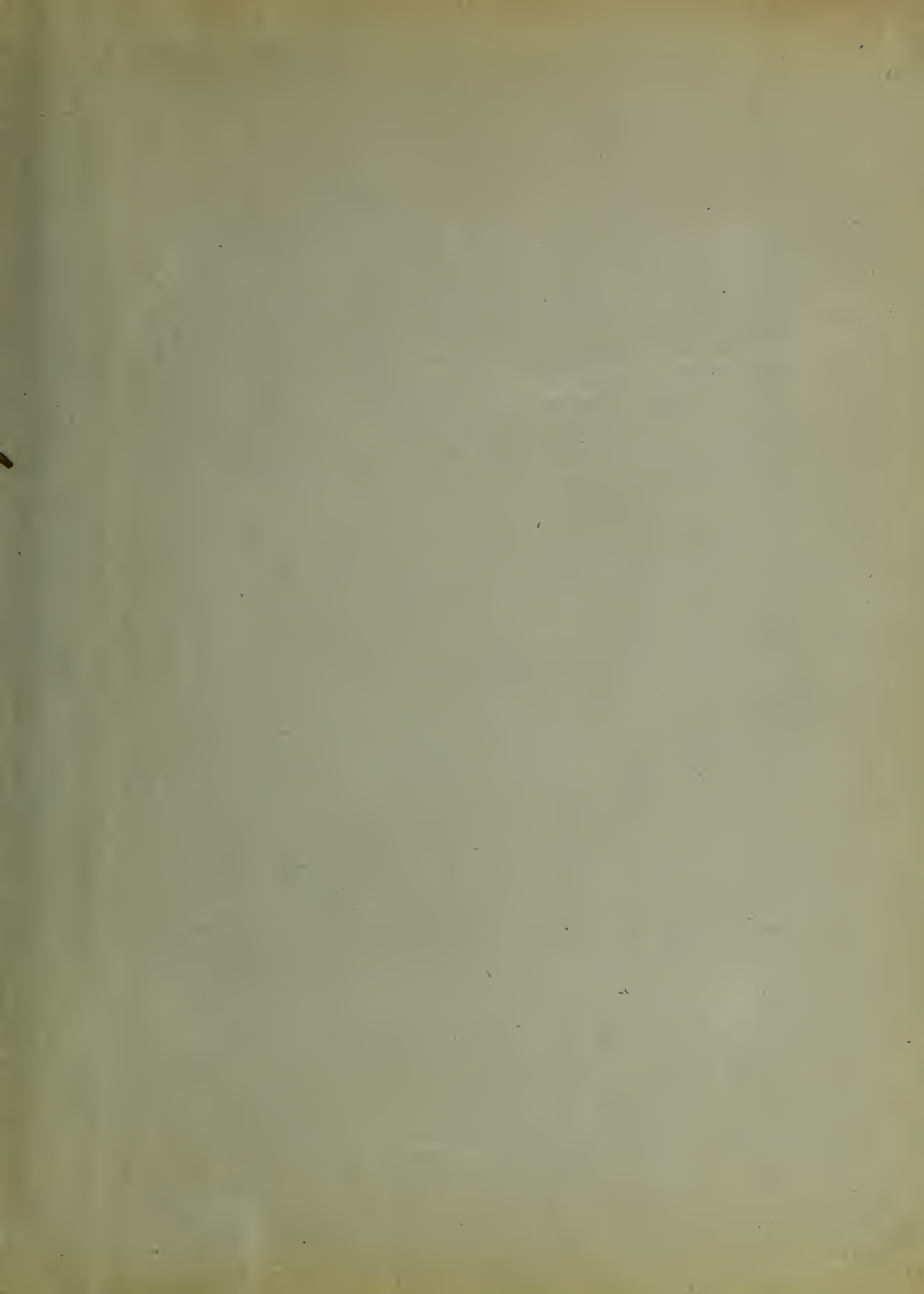


Fig. 145. Arrangement of capsules for experiments with circular plates.

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Fig. 146. Sand Ballast. Circular Plate Experiments.



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